Cold Nuclear Matter Effects and Heavy Quark Production in PHENIX

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On behalf of the PHENIX collaboration

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Heavy quark production in nuclear collisions

Like jets, heavy quarks are an attractive probe of the matter formed in heavy ion collisions because they are produced in **hard processes** that occur only during the nuclear crossing.

Heavy quark distributions in nuclear collisions are different from those in p+p due to:

- Modification of the production cross section in a nuclear target – **cold nuclear matter** (CNM) effects
- Modification of the observed distributions due to interactions with the final state medium – **medium effects**

- Both occur in A+A collisions.
- Only CNM effects occur in p(d)+A collisions.

Cold nuclear matter effects

Generally depend on rapidity, p_T, and mass of the probe.

CNM effects include

- **Shadowing** – modified (effective) parton distributions in nuclei
- Initial state energy loss of partons
- Cronin effect – multiple elastic scattering of partons
- **Breakup** of precursor quarkonia by nucleon collisions during the nuclear crossing

The strength of the initial state energy loss and Cronin effects do not seem to be well estalished.

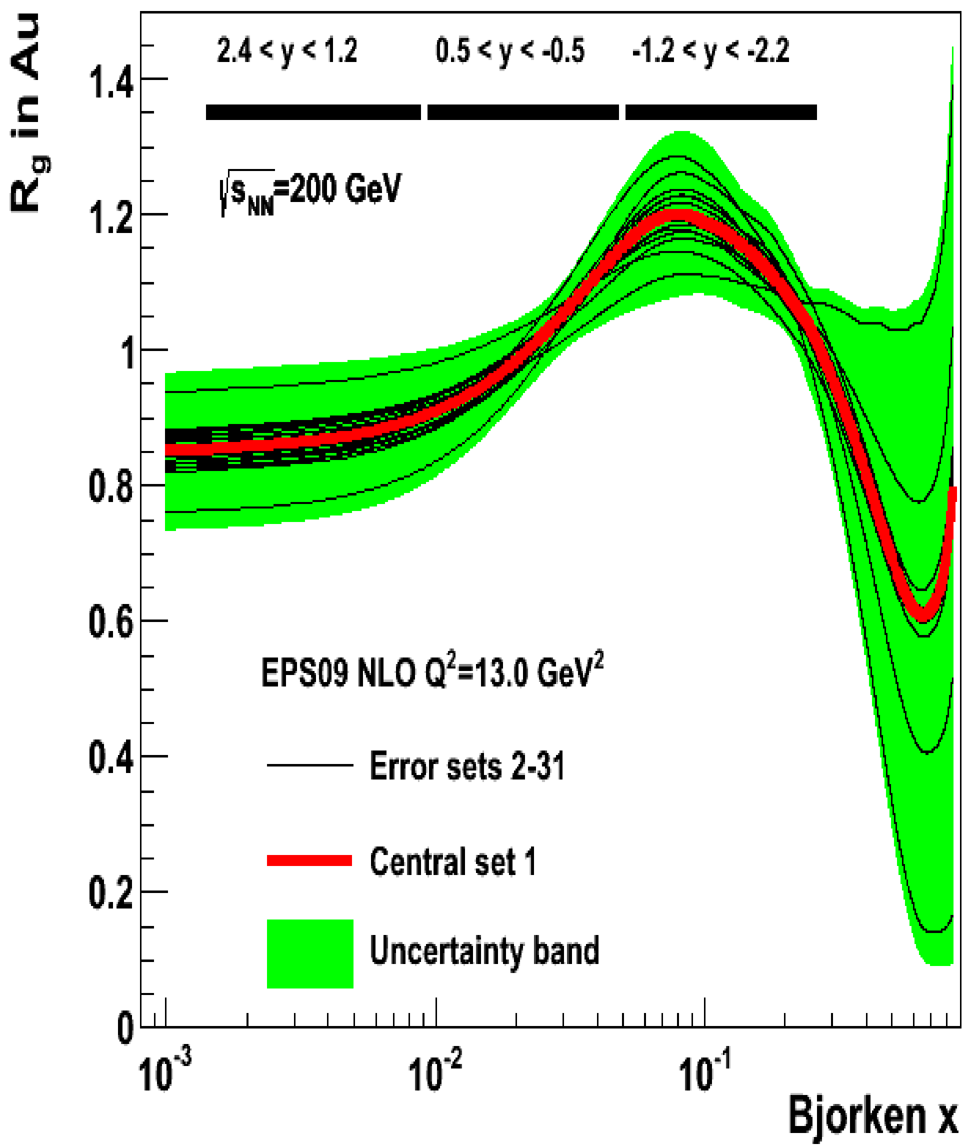
Shadowing – modifies the (effective) parton density

Parameterized from DIS and p+A data. EPS09 is a recent example.
Impact parameter dependence unknown.

However, see Kari Eskola's talk tomorrow for new developments!

gluon modification vs Bjorken x for **J/ψ production**
(Assuming 2→1 kinematics)

$$x_2 = \frac{\sqrt{M^2_{J/\psi} + p^2_T}}{\sqrt{s_{NN}}} e^{-y} \qquad Q^2 = M^2_{J/\psi} + p^2_T$$



J/ψ breakup cross section energy dependence from p(d)+A

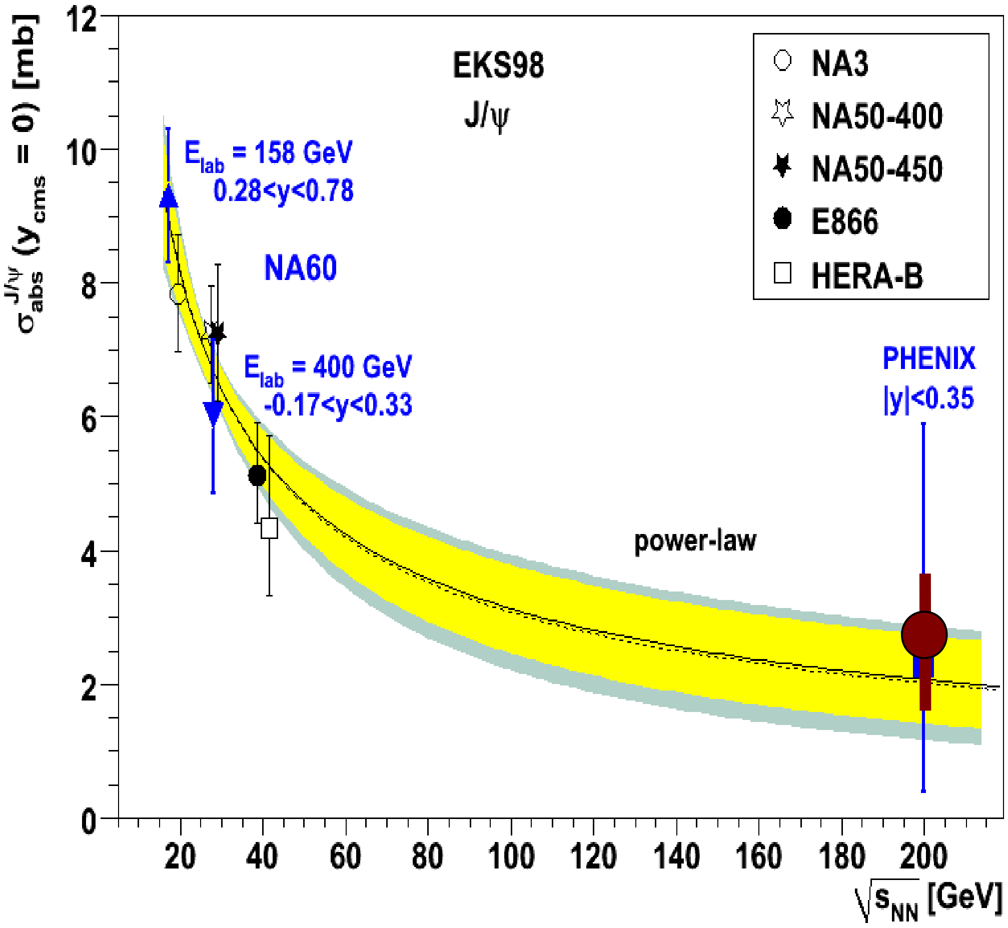
Systematic analysis by Lourenco, Woehri and Vogt at **y~0** using EKS98 nPDF's + fitted σ_{br}.

Clear **collision energy dependence** of σ_{br}.

Added PHENIX point is from the 2008 run (2.7 +1.1 -1.2 mb) (from fit by ADF using EKS98 calculations from Ramona Vogt).

σ_{br} may depend on rapidity (and p_T?) also.

JHEP 0902:014 (2009)



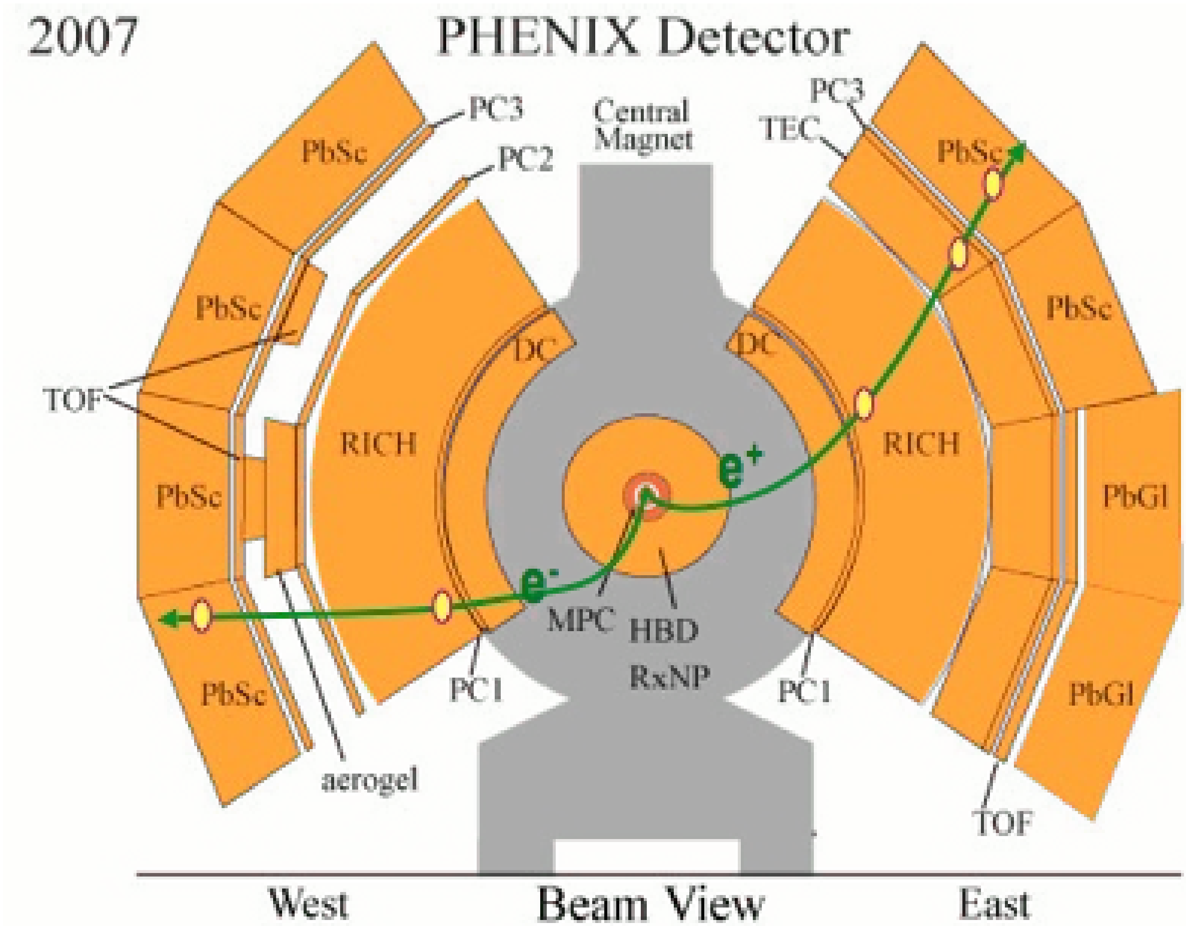
Note: this suggests strongly that σ_{br} will likely be smaller at the LHC.

PHENIX experimental capabilities

Observing HF via electron decays (y~0)

Central arms (mid rapidity, as of 2008 Run)

- Drift chamber + Pad Chamber (momentum measurement)
- Ring Imaging Cherenkov detector (hadron rejection ~ 100)
- Electromagnetic Calorimeter (E/p → hadron rejection ~ 10)



D, B → $e^{\pm}$

$J/\psi \rightarrow e^+e^-$

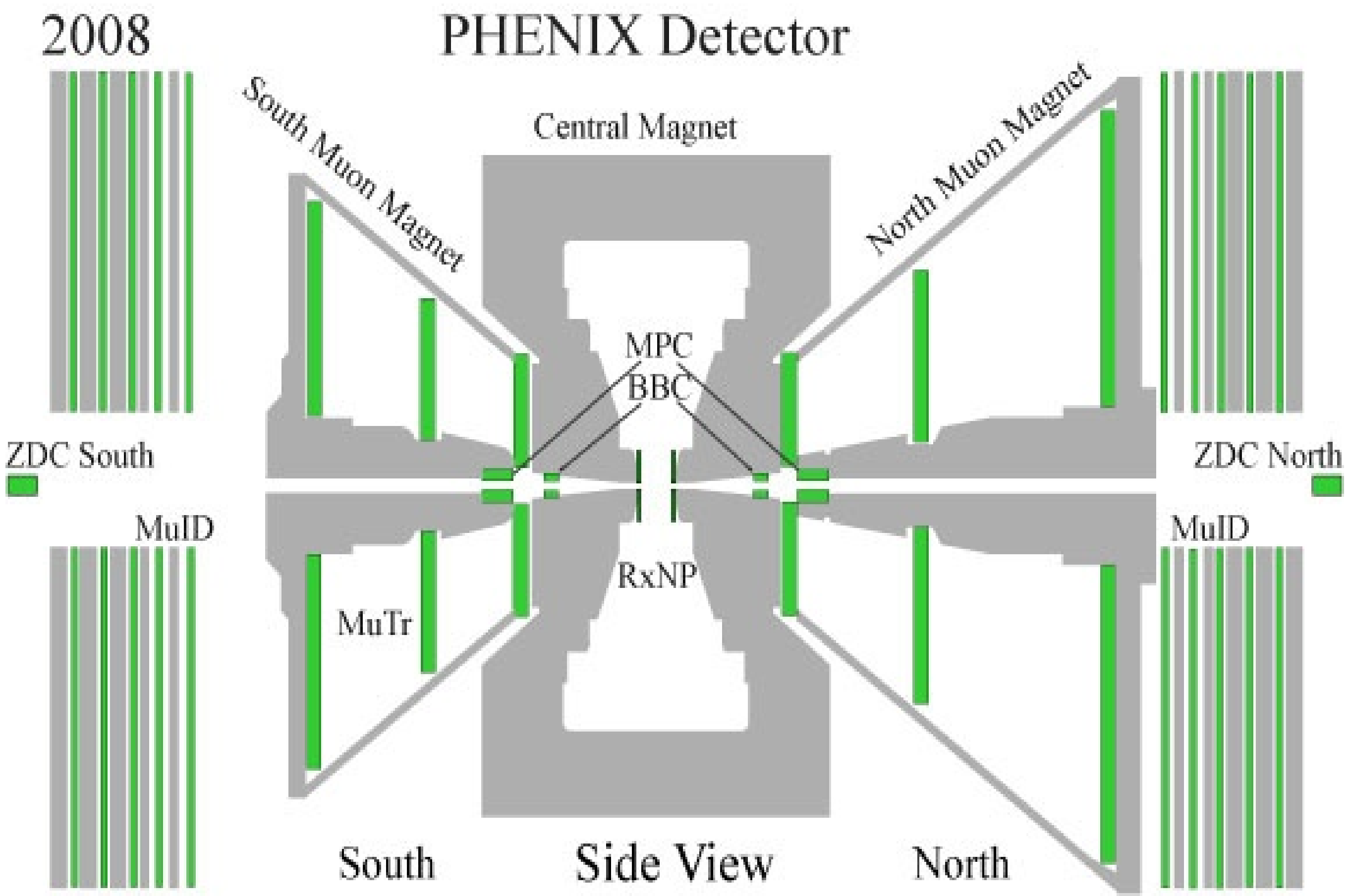
$-0.35 < y < 0.35$

$\Delta\Phi = \pi$

Observing HF via muon decays (1.2<|y|<2.2)

Muon arms (forward and backward rapidity)

- Muon Tracker (momentum)
- Steel absorber (shower out hadrons)
- Muon Identifier (layered [steel absorbers / wire chambers] for muon ID)



D, B → $\mu^{\pm}$

J/ψ → $\mu^{+}\mu^{-}$

$-2.2 < y < -1.2$

$1.2 < y < 2.4$

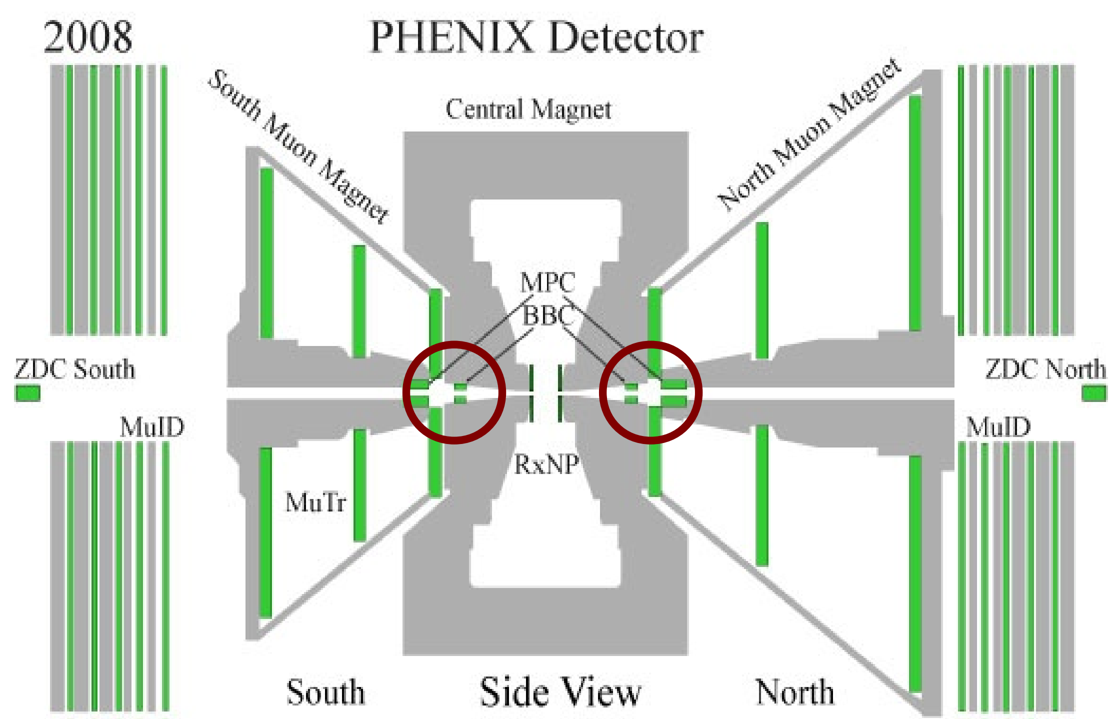
$\Delta\Phi = 2\pi$

The Beam-Beam Counters (BBC)

Cover $3.0 < |\eta| < 3.9$.

Detect soft charged particles produced in a collision, and provide:

- The minimum bias **event trigger**
- The collision **Z vertex** (from Δt between BBC North and South)
- The collision **centrality** for A+A collisions (from the signal size)



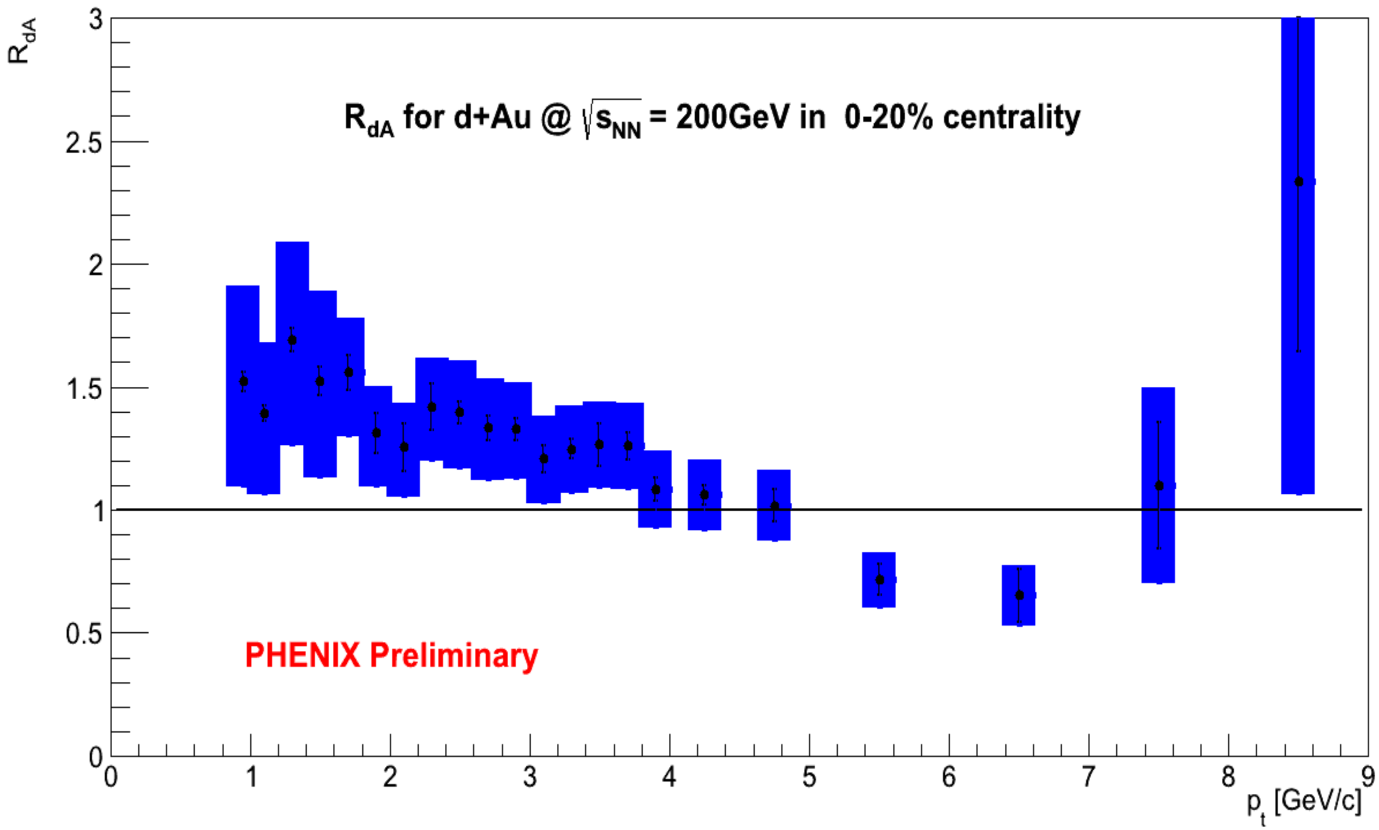
Studying CNM effects using data from d+Au collisions

Preliminary open heavy flavor R_{dAu}

Semileptonic open heavy flavor decay R_{dAu} at 200 GeV at y=0.

Indication of an excess at 1-4 GeV/c, but not far outside the systematics. **No suppression** seen up to 5 GeV/c though.

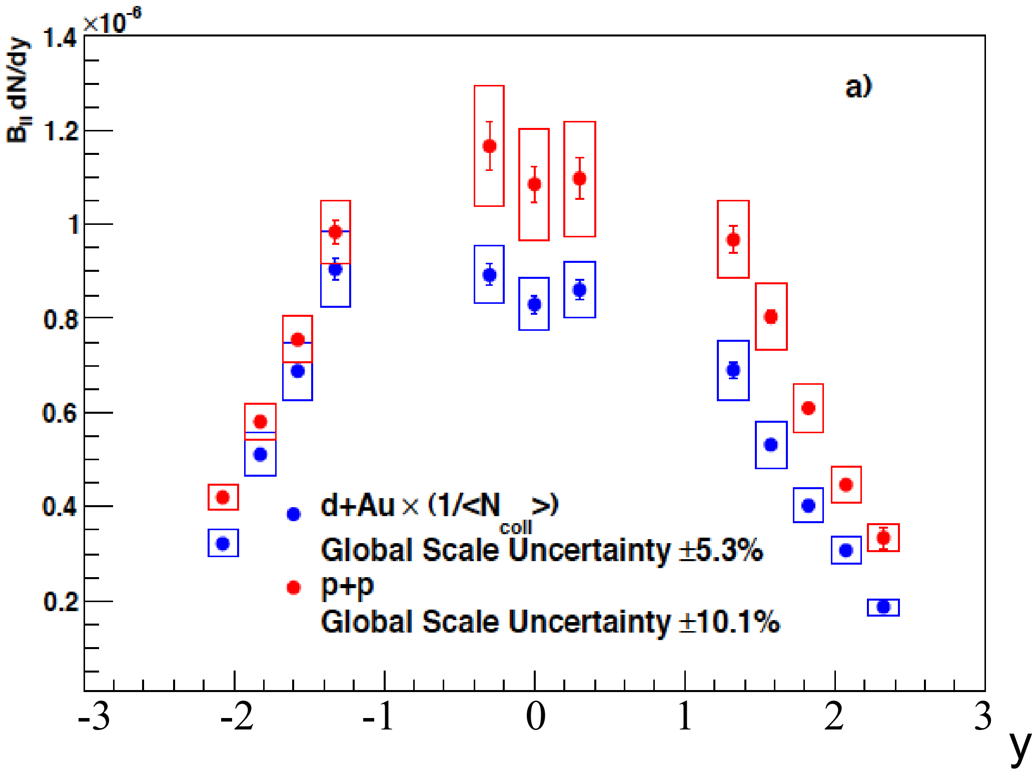
Final data should be published very soon.

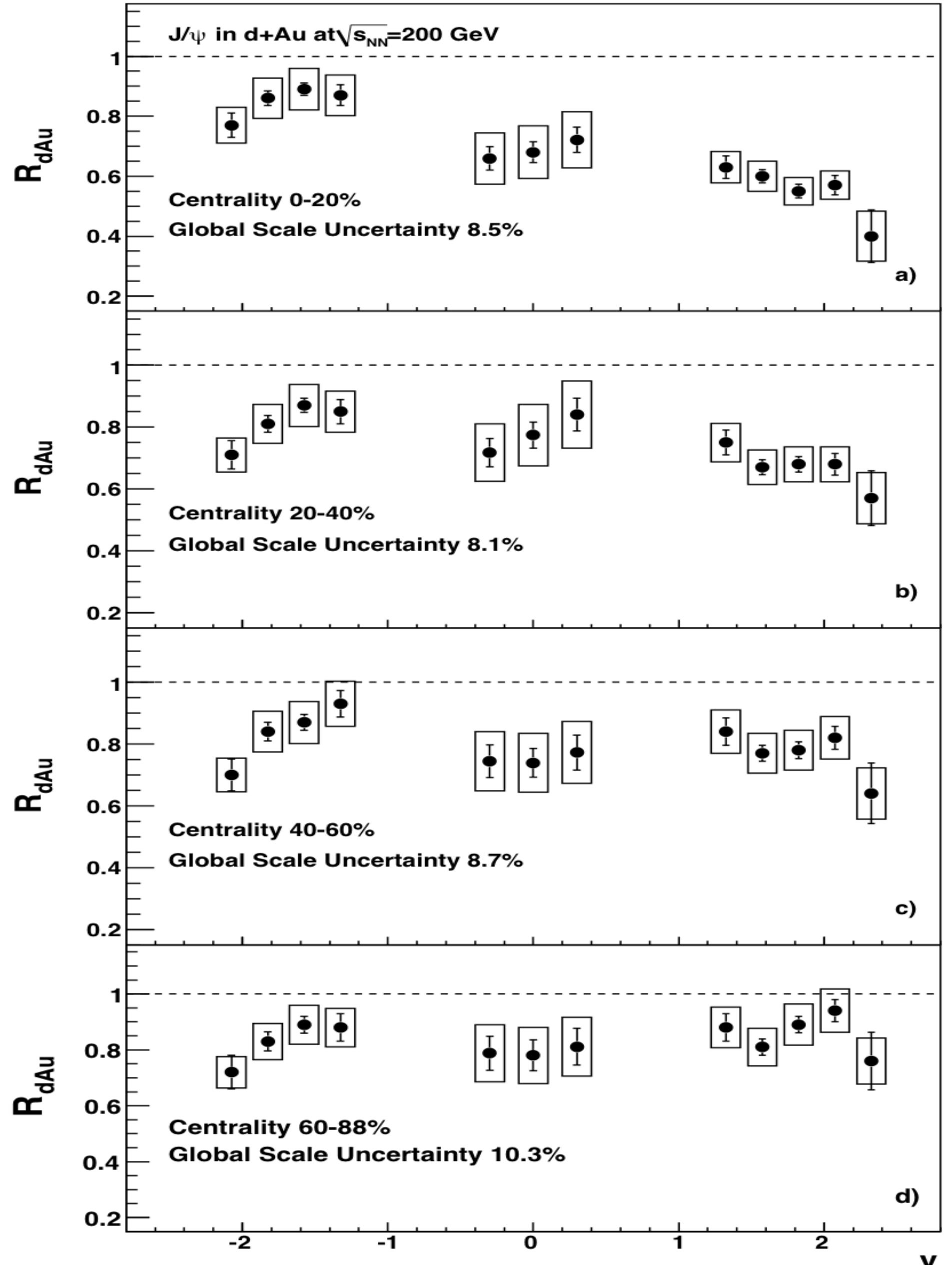


PHENIX 2008 run d+Au J/ψ rapidity dependence

PHENIX d+Au J/ψ results from Run 8. R_{dAu} in **four centrality bins**, at **12 rapidities** from -2.075 to + 2.325.

The three rapidity bins near y=0 are from electrons in the central arms. The other 9 bins are from the muon arms.



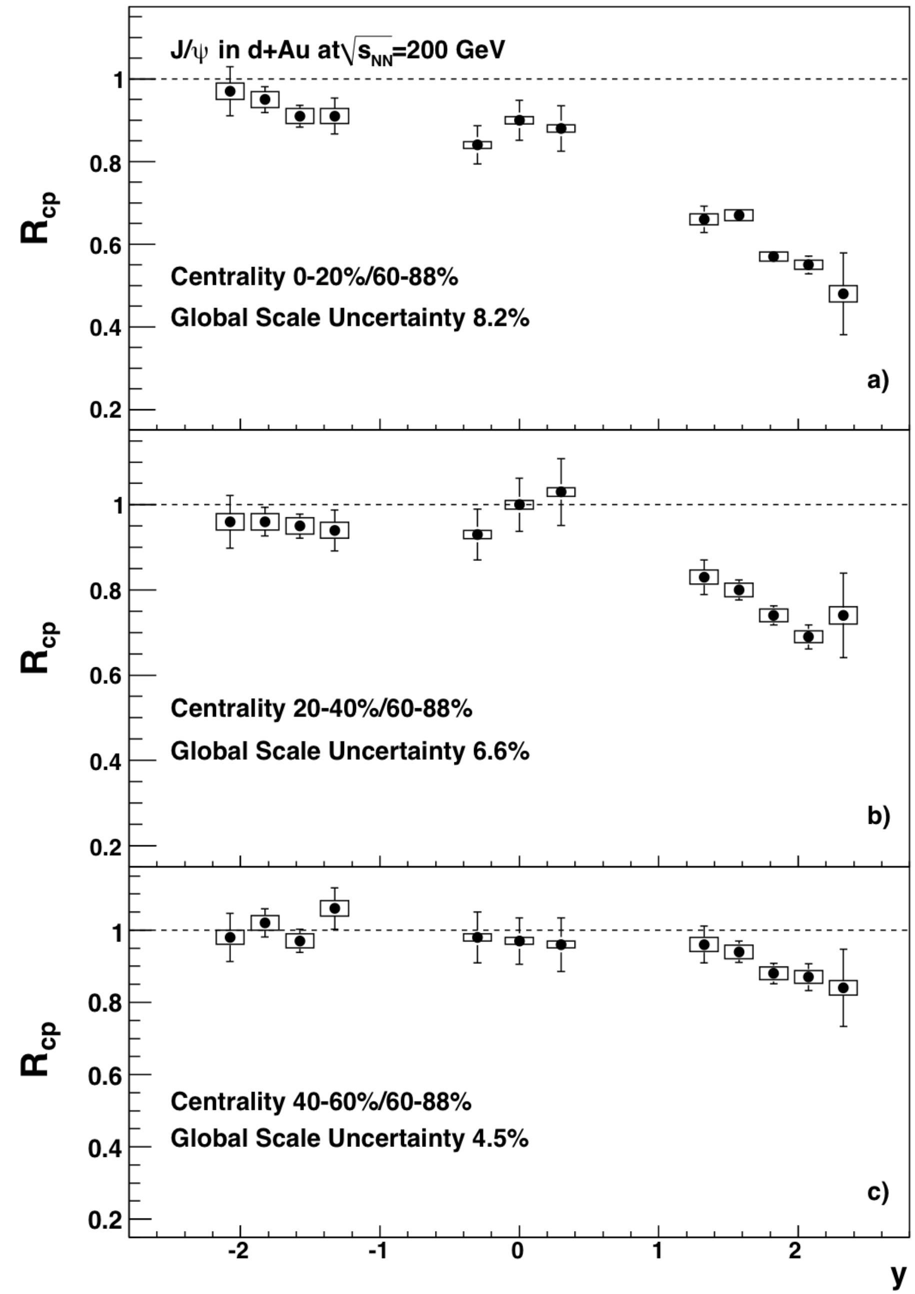


PHENIX: PRL 107 (2011) 142301

R_{CP} for d+Au J/ψ vs rapidity

The ratio R_{CP} cancels out many experimental systematic uncertainties, at the expense of the loss of the peripheral bin modification.

Later, we see that the **combination** of R_{dAu} and R_{CP} is powerful.



Define nuclear thickness Λ for each N-Au collision

Define the longitudinal density integrated nuclear thickness in Au at **impact parameter r_T**. It has units fm^{-2}:

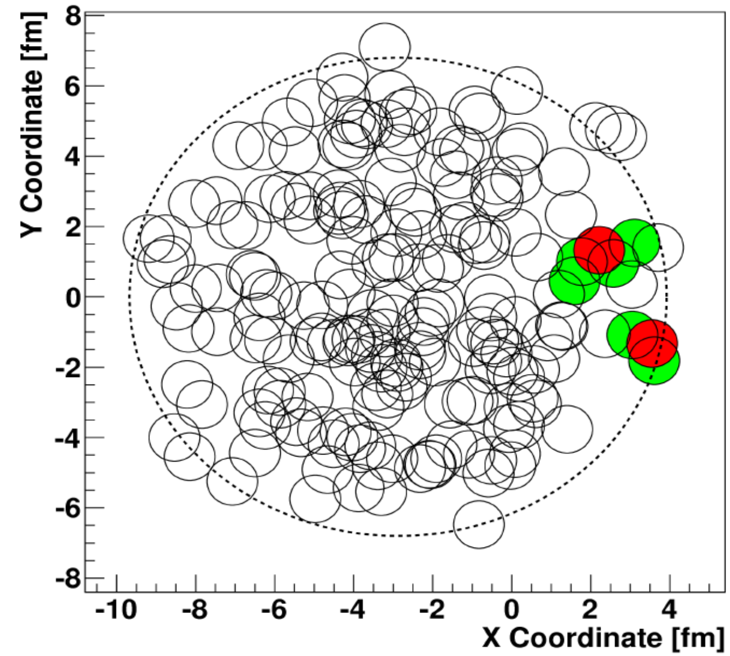
$$\Lambda(r_T) = \int dz\, \rho(z, r_T)$$

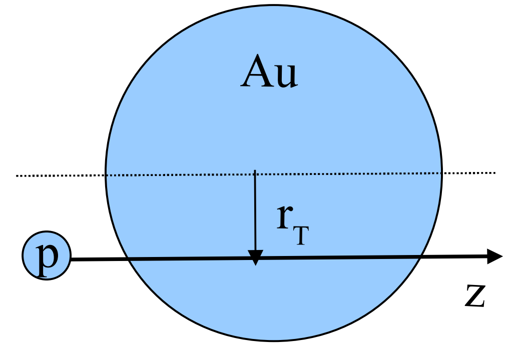
Where z is the longitudinal distance in the projectile direction and $\rho(z,r_T)$ is the nuclear density at z and r_T, obtained from a Woods Saxon distribution.

Assume that CNM effects are related to Λ at the r_T value for each nucleon.

Use a Glauber calculation to average a **postulated CNM effect** over the PHENIX centrality bins.

Snapshot of dAu collision in Glauber model





An interesting result

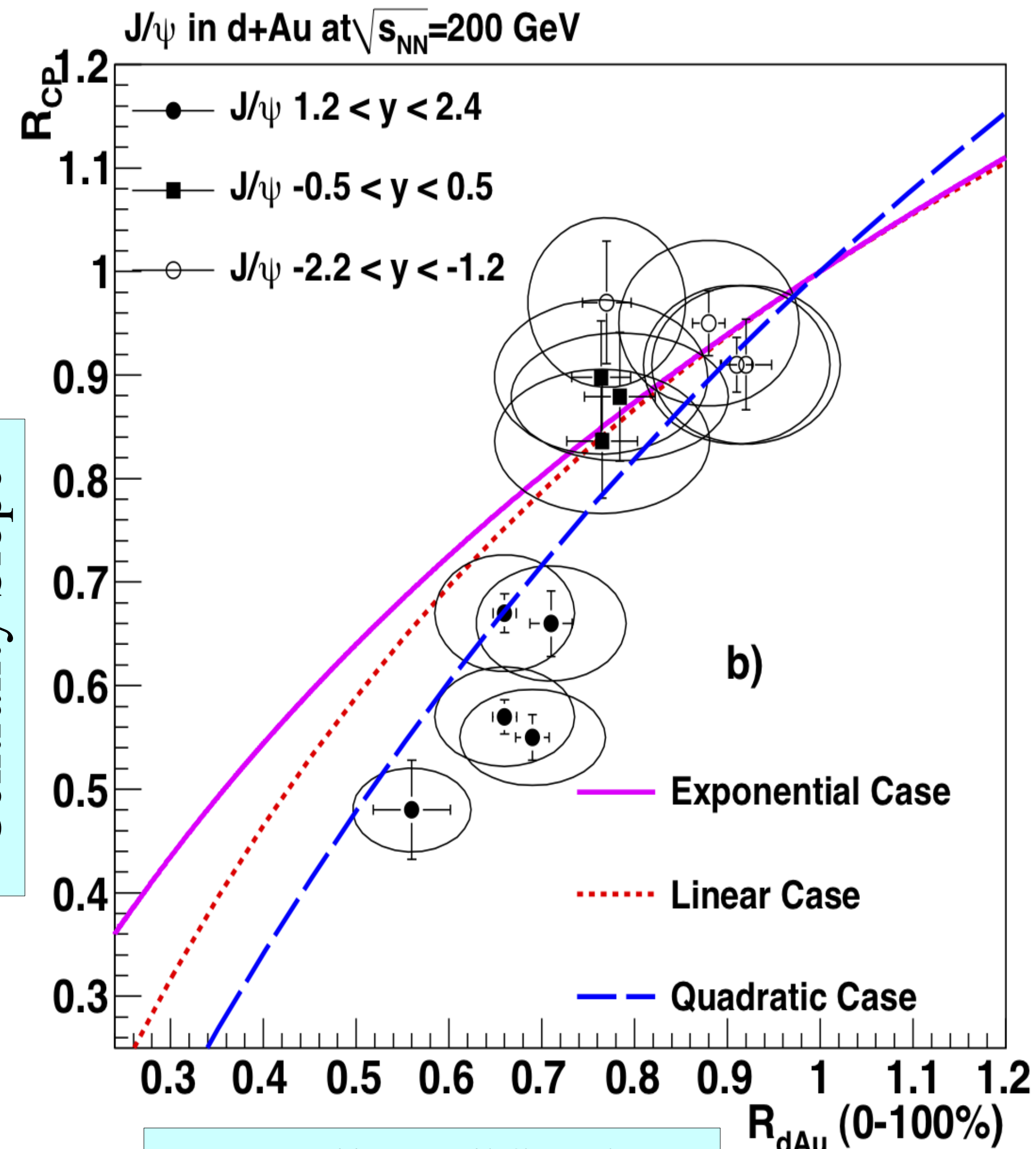
R_{dAu} (0-100) **vs** R_{CP} (0-20/60-98)
Circles are systematic uncertainties

Data compared with some simple **mathematical** forms for the modification vs nuclear thickness, in a Glauber model.

$$M(r_T) = e^{-a\Lambda(r_T)}$$
$$M(r_T) = 1 - a\Lambda(r_T)$$
$$M(r_T) = 1 - a\Lambda(r_T)^2$$

The forward rapidity data points are barely consistent with even a pure quadratic thickness dependence.

PHENIX: PRL 107 (2011) 142301



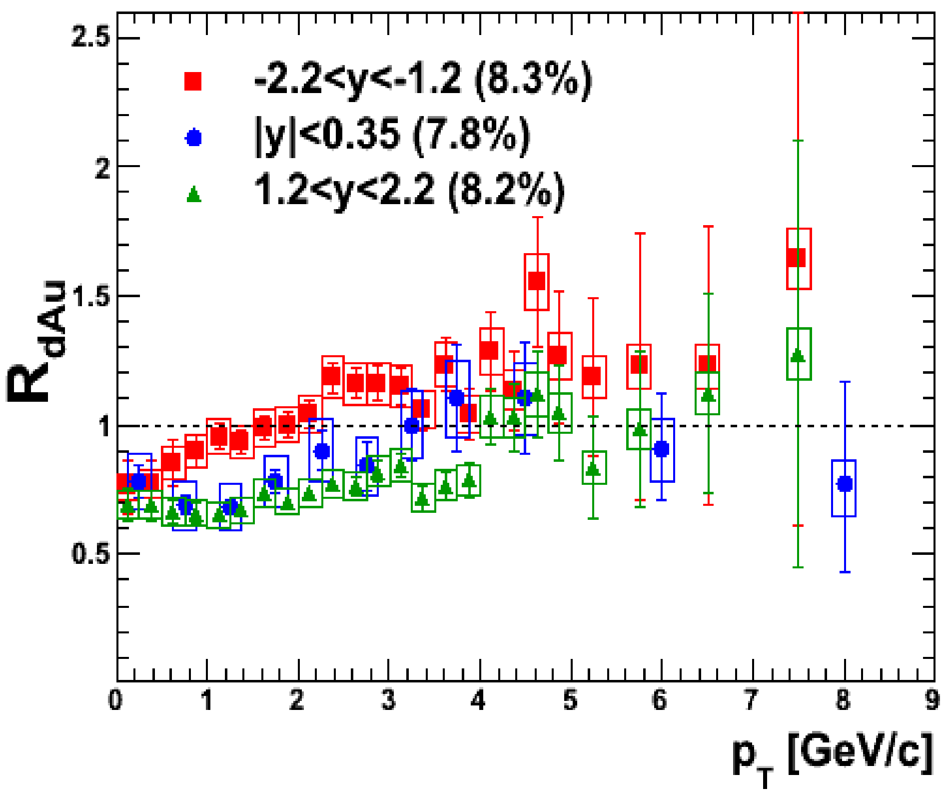
Centrality Slope

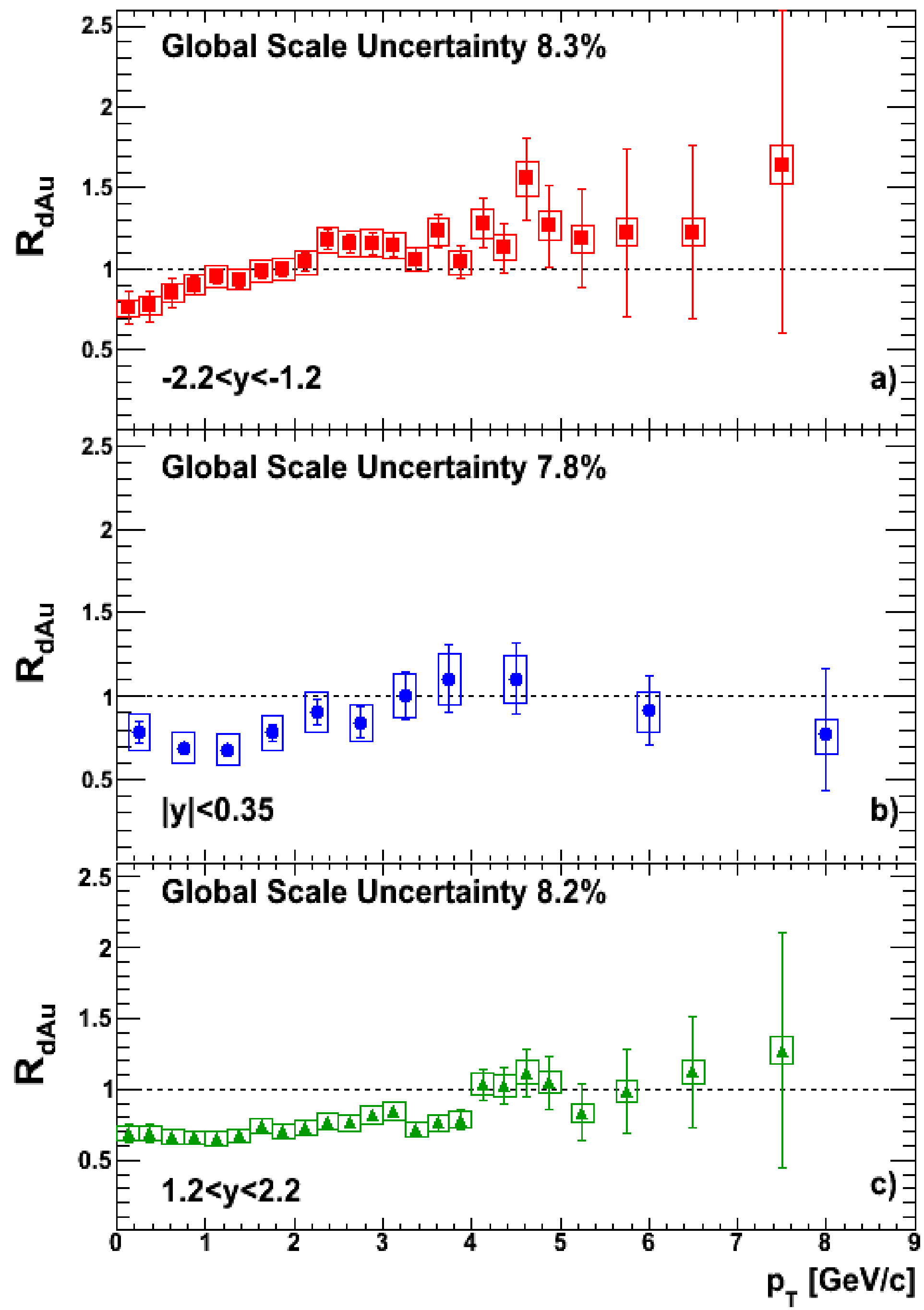
Overall modification

New results - p_T dependence of R_{dAu} for J/ψ

Similar behavior at mid (blue) and forward (green) rapidity.

Rather different at backward rapidity (red).

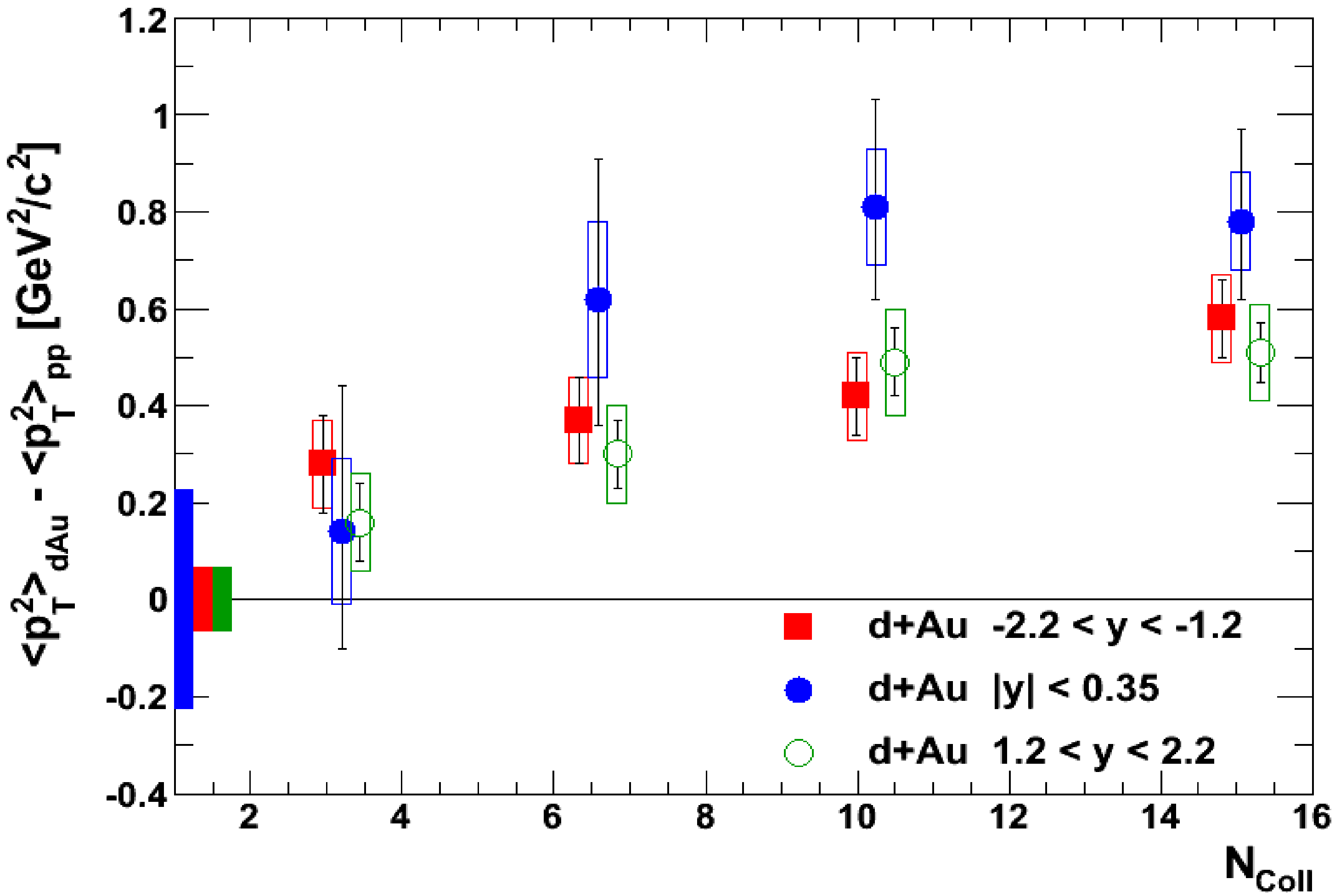




The $\langle p_T^2 \rangle$ enhancement increases with collision centrality

The difference in $\langle p_T^2 \rangle$ values between d+Au and p+p, plotted versus collision centrality, behaves similarly at all three rapidities.

Note: Midrapidity is "harder", so the actual $\langle p_T^2 \rangle$ is larger there too.

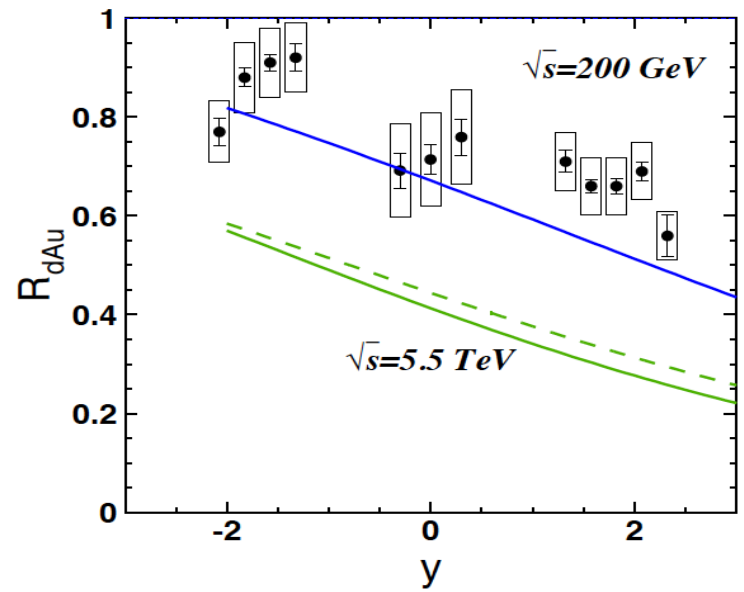


Models of J/ψ production in d+Au

Model of the color dipole breakup:

Kopeliovich et al., NP A864 (2011) 203

- Color dipole σ_{cc} (r_T,x) from HERA data.
- Cronin parameterized from low energy data
- Shadowing correction from nDSg
- with 2→1 kinematics



Models with nPDF's + effective σ_{br} + …

Lansberg et al. arXiv:1201.5574, PLB 680, 50 (2009):

- EKS98, nDSg, or EPS08 with 2→2 kinematics from Color Singlet Model
- Range of σ_{br} = 0, 2.6 4.2 or 6 mb independent of p_T or y
- No added Cronin effect or initial state energy loss

Nagle et al., PRC 84 (2011) 044911

- EPS09 + σ_{br} = 0-20 mb, independent of p_T or y
- Tried initial state energy loss

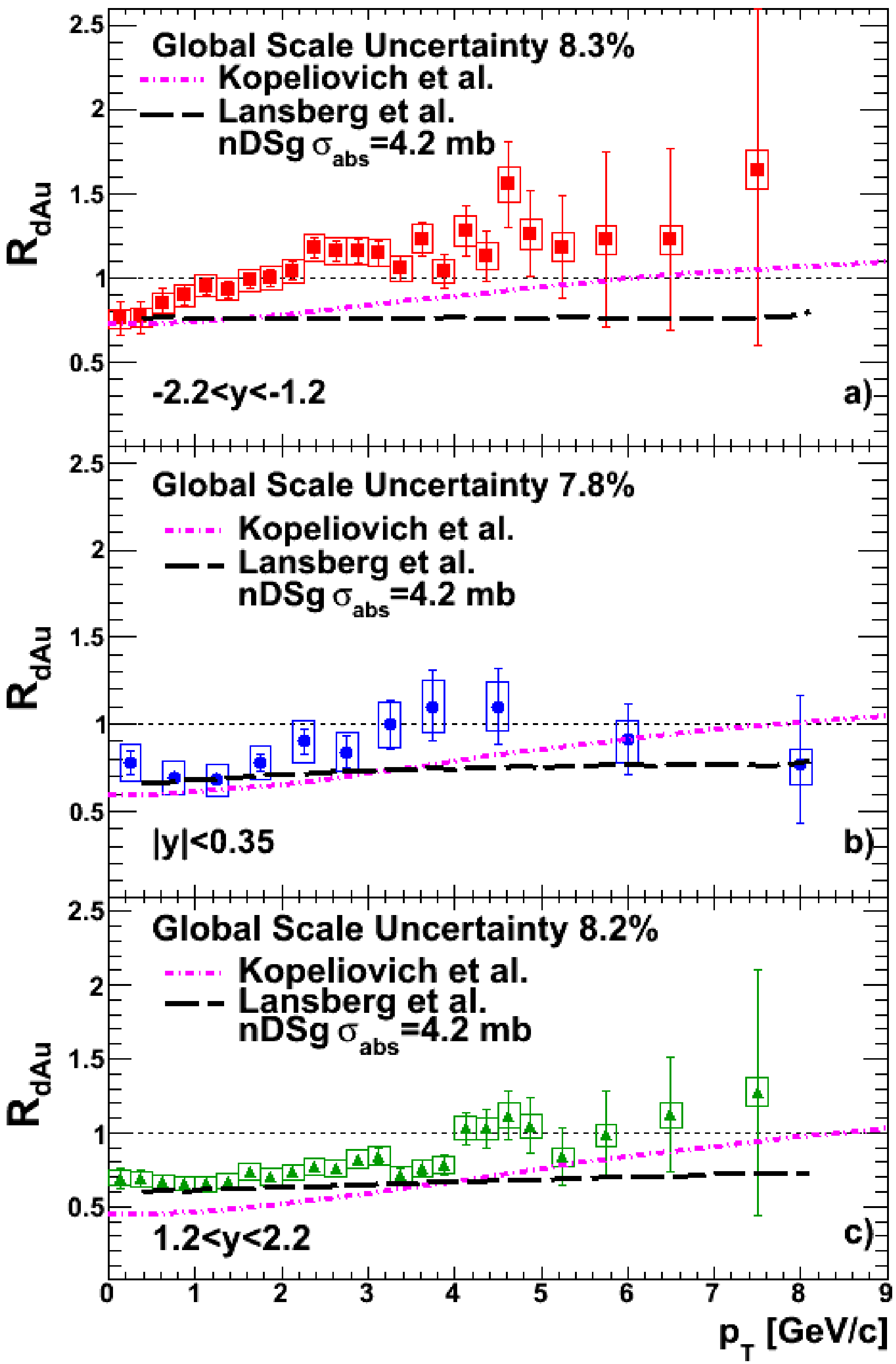
Models of J/ψ production in d+Au (cont.)

Model of the shadowing
(Coherent scattering / Color Glass Condensate model)
Kharzeev et al., arXiv:1205:1544
(calculations restricted to forward rapidity by model assumptions

0-100% unbiased J/ψ data

Both models use **nDSg for shadowing**. The stronger modulation with p_T of Kopeliovich et al. is presumably due to the added Cronin effect (although an effect from the different kinematics assumptions is possible).

Models do **not** do well for backward rapidity. Problem with the nPDF's?



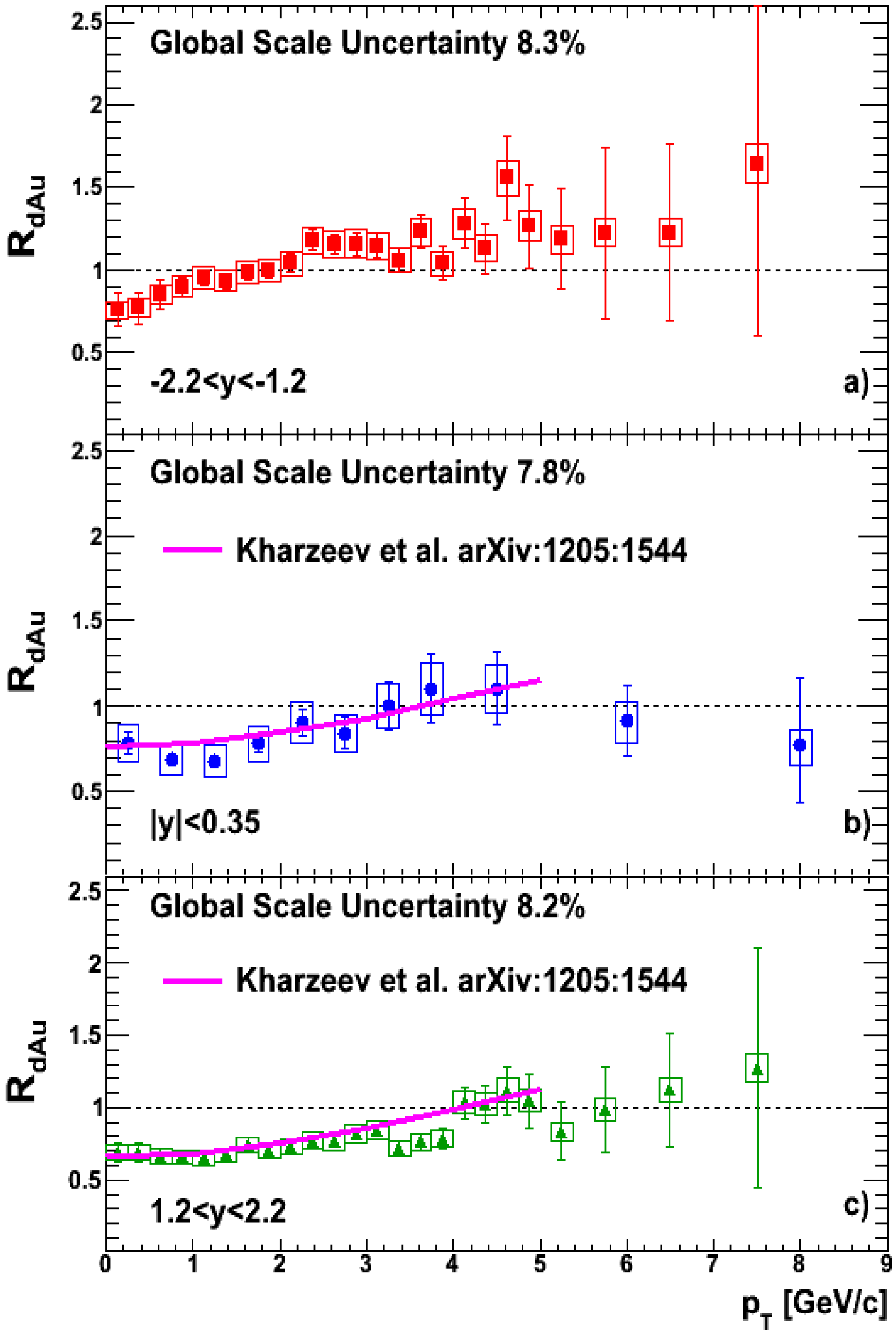
0-100% unbiased J/ψ data

Kharzeev et al., arXiv:1205:1544

At RHIC energies the model is:

- not applicable at $y<0$
- "marginally applicable" at $y \sim 0$
- applicable at $y > 0$, $p_T < 5$ GeV/c

Centrality dependence?

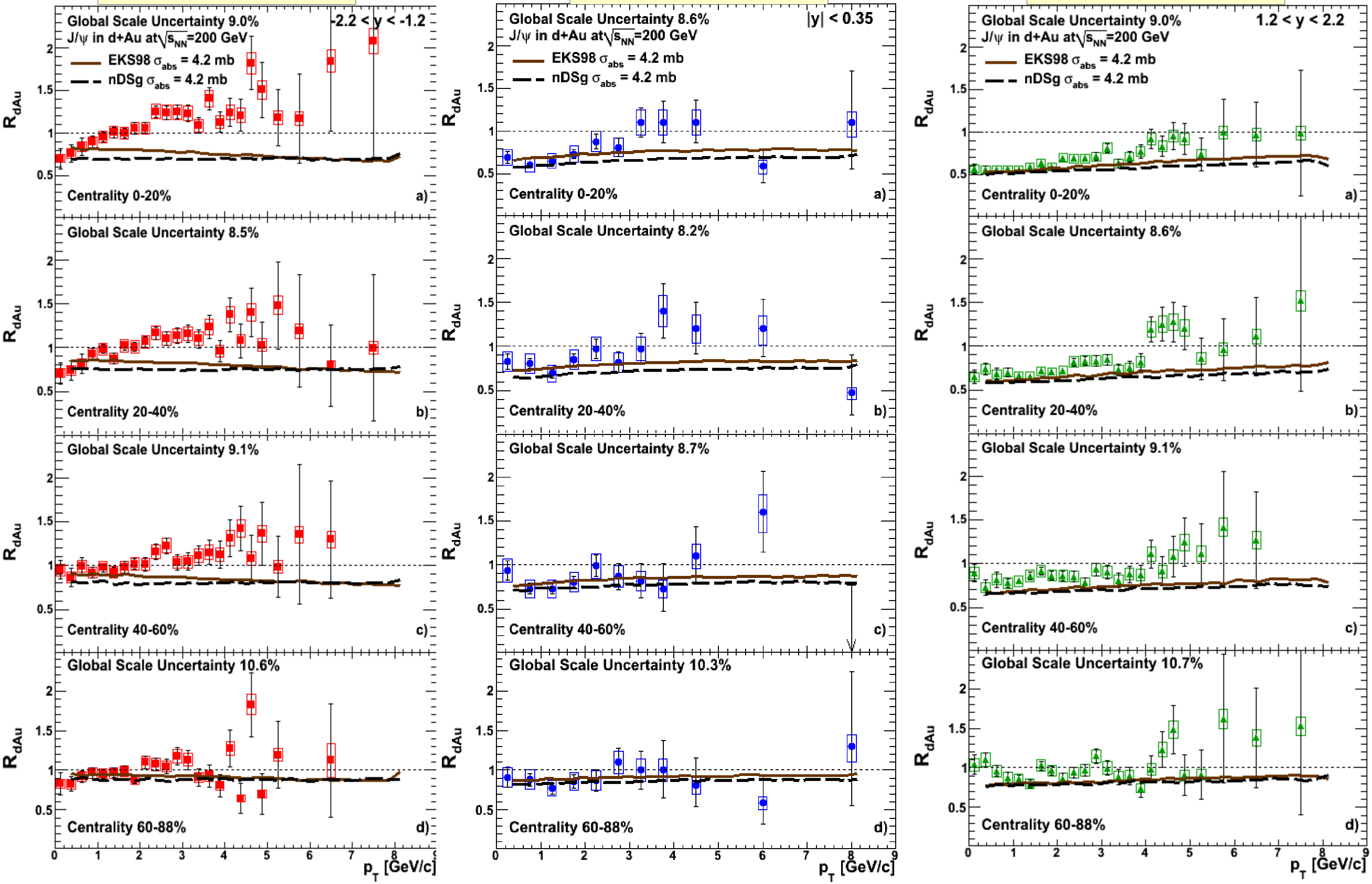


Lansberg et al.-nDSg/EKS98+linear thickness dependence

-2.2<y<-1.2

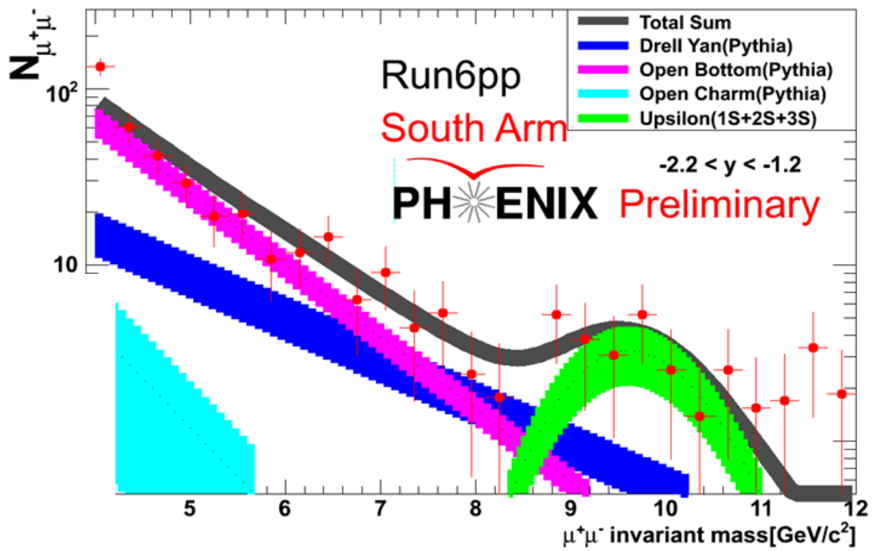
-0.35<y<0.35

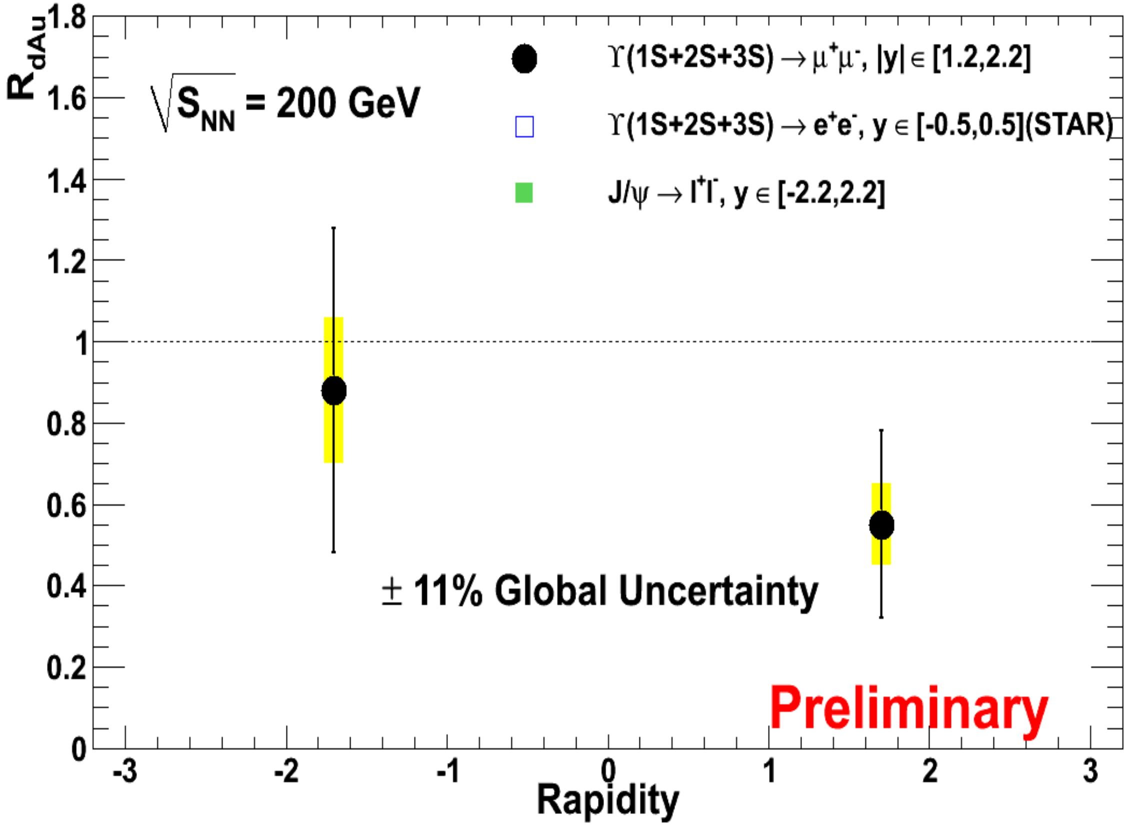
1.2<y<2.2

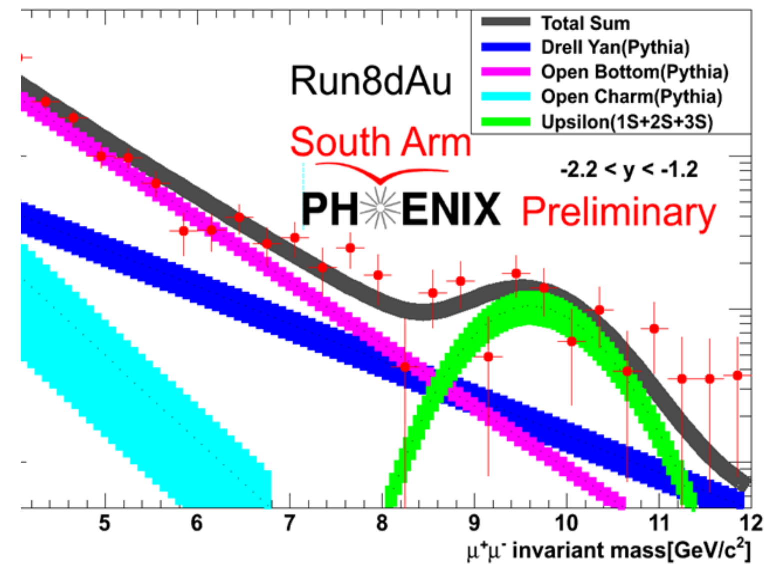


Upsilon(1S+2S+3S) R_{dAu}

Y(1S+2S+3S) preliminary data at forward and backward rapidity.

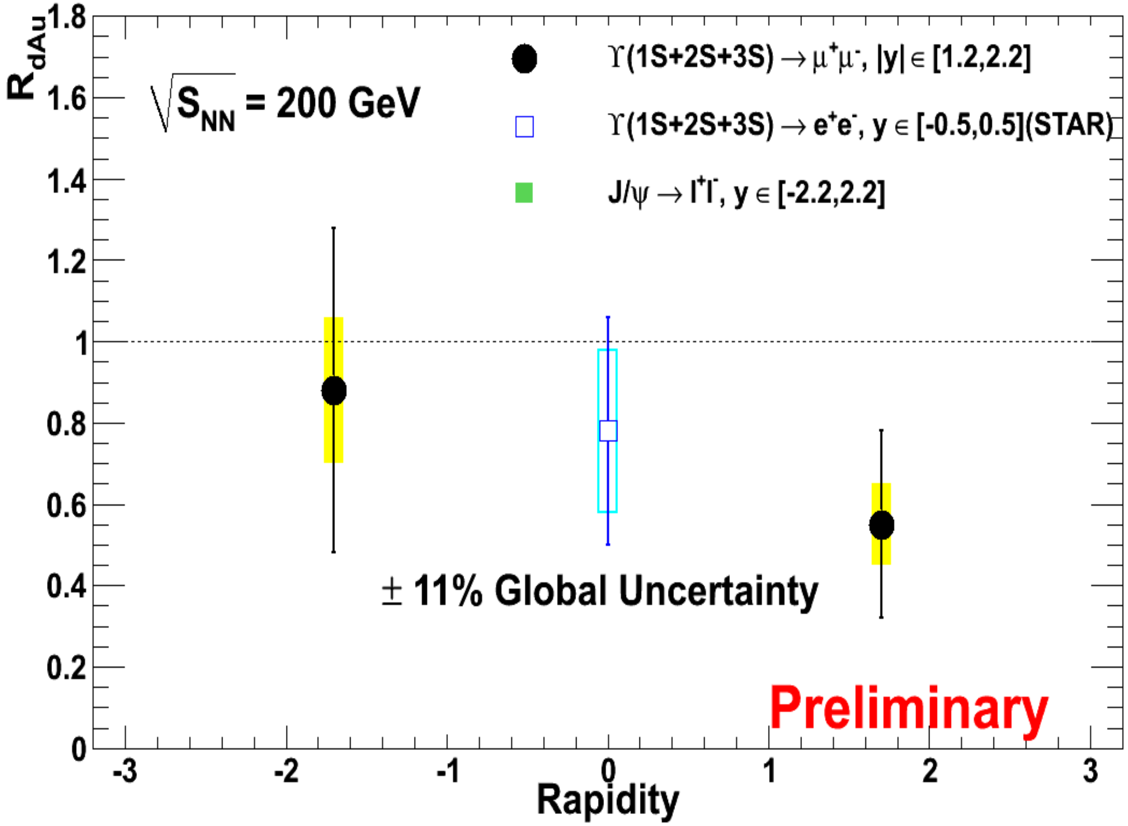


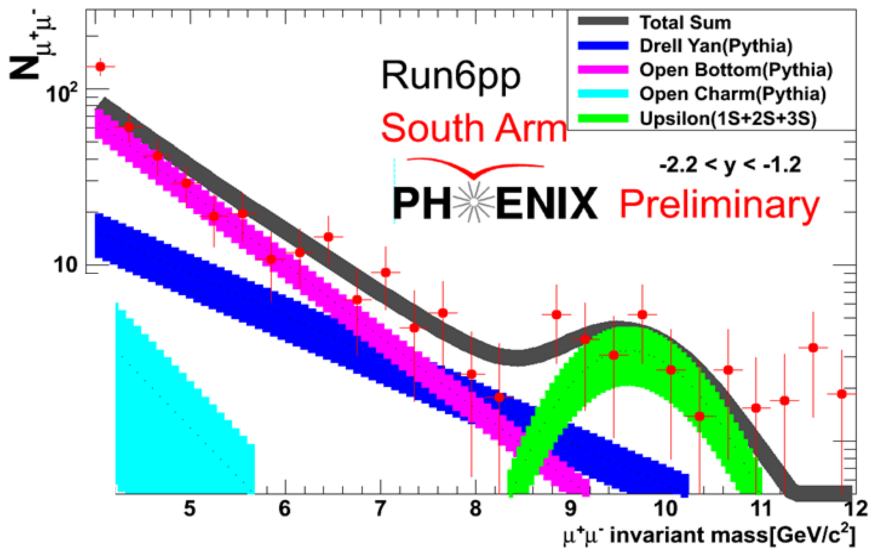


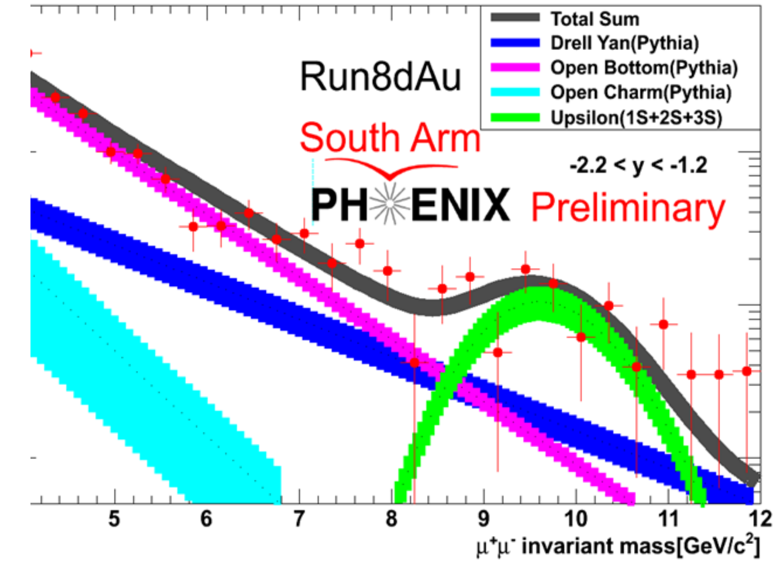


Upsilon(1S+2S+3S) R_{dAu}

Y(1S+2S+3S) preliminary data.
Add STAR preliminary at y=0.
(PHENIX data at y=0 coming soon)







Upsilon(1S+2S+3S) R_{dAu}

Y(1S+2S+3S) preliminary data.
Add STAR preliminary at y=0.
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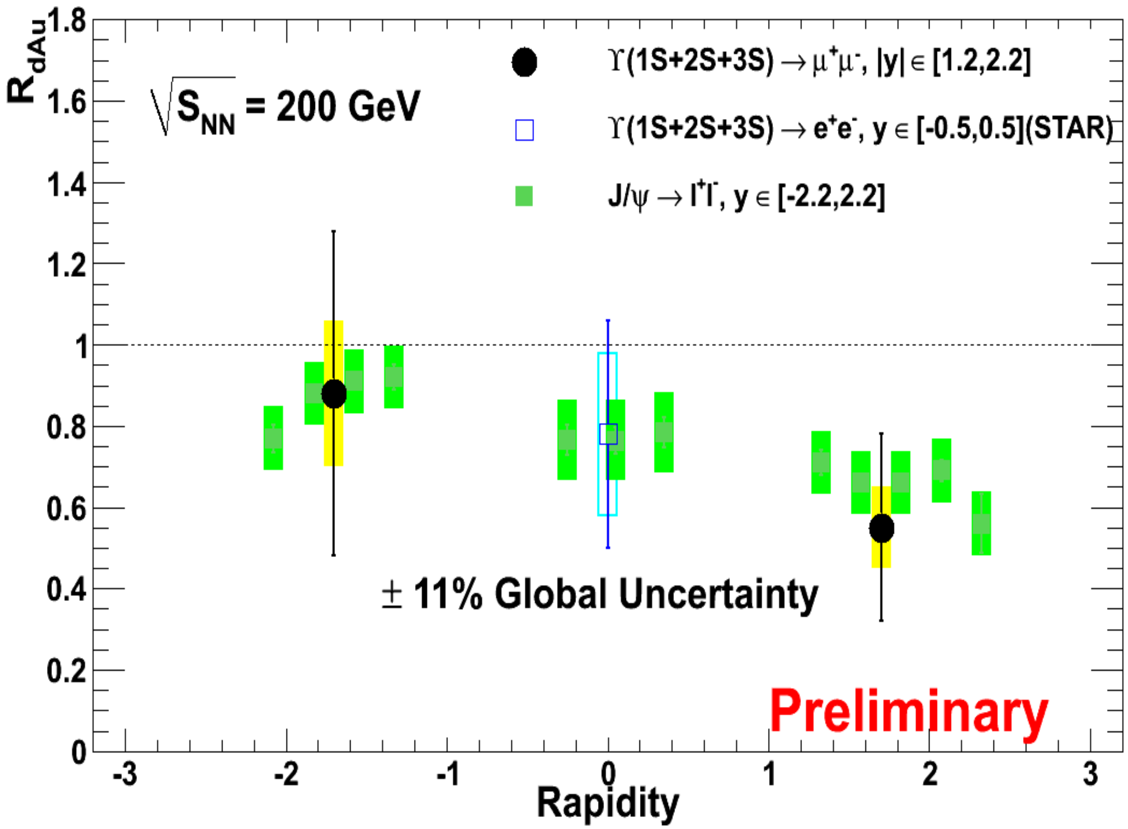
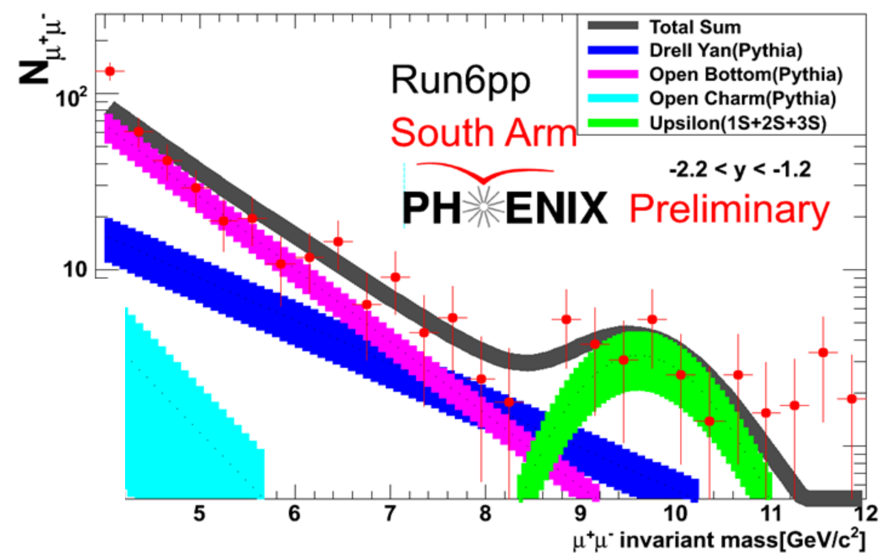
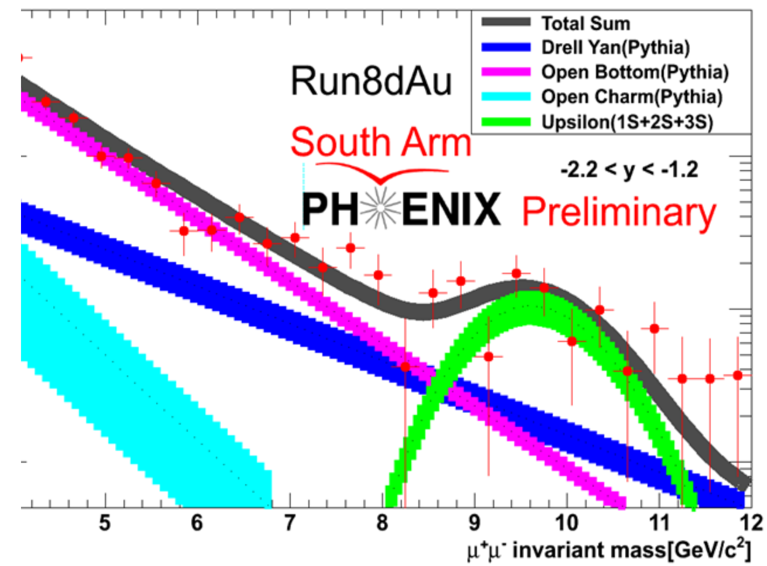
Compare with PHENIX **J/ψ** data.







Upsilon(1S+2S+3S) R_{dAu}

Y(1S+2S+3S) preliminary data.
Add STAR preliminary at y=0.
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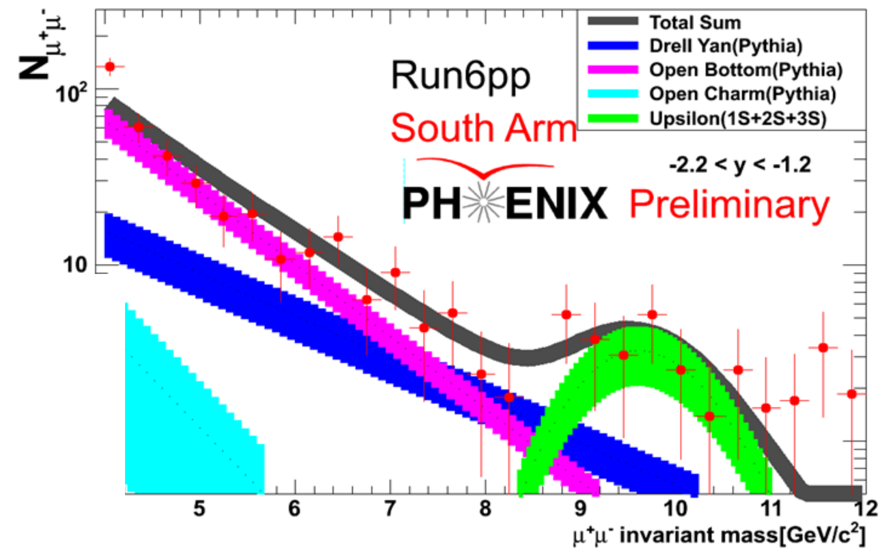
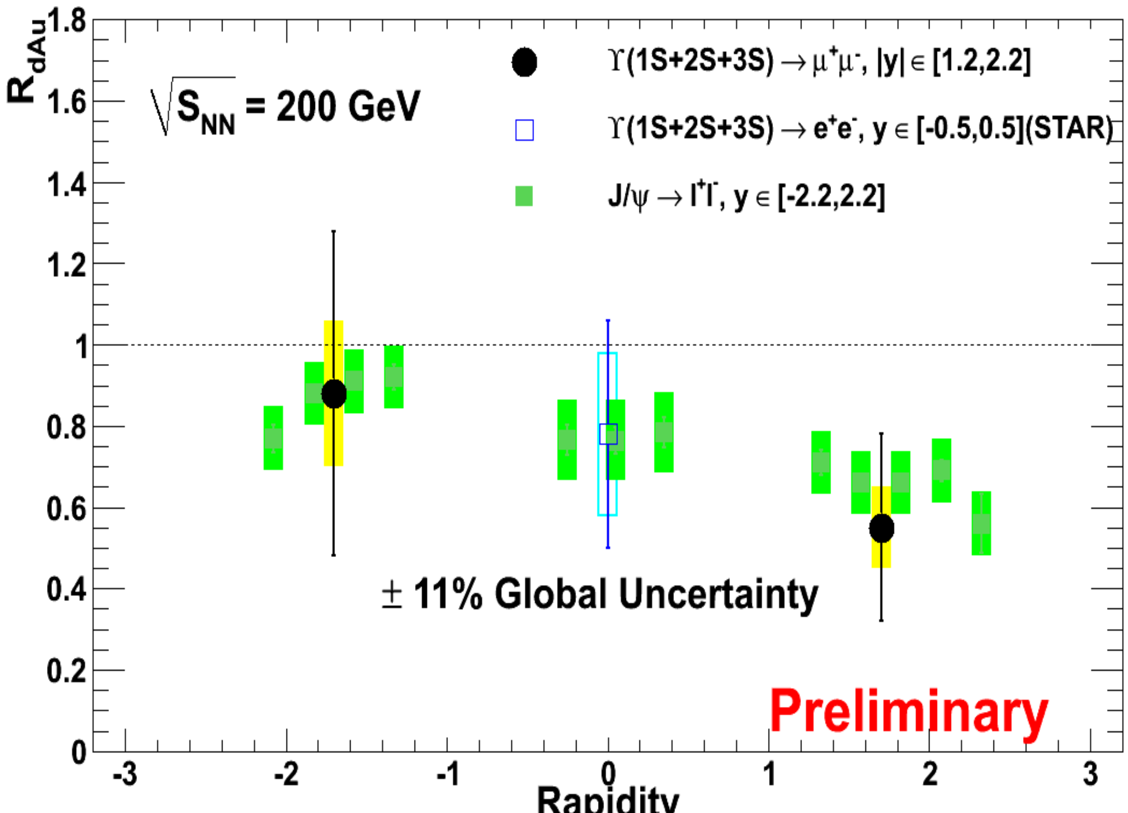
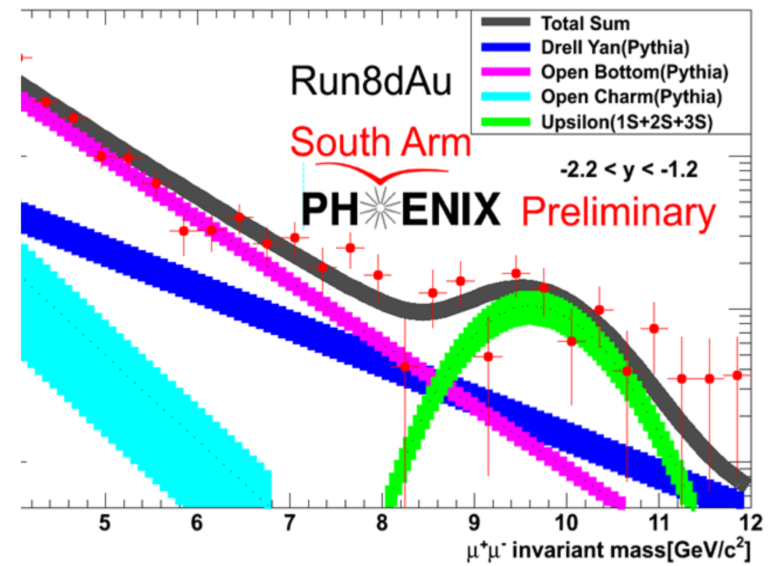
Compare with PHENIX **J/ψ** data.

Final Y(1S+2S+3S) results soon







Conclusions from d+Au data

Open heavy flavor:

- No suppression for 1-5 GeV/c, likely some enhancement.
- Final data out soon, VTX data next d+Au run!

Quarkonium:

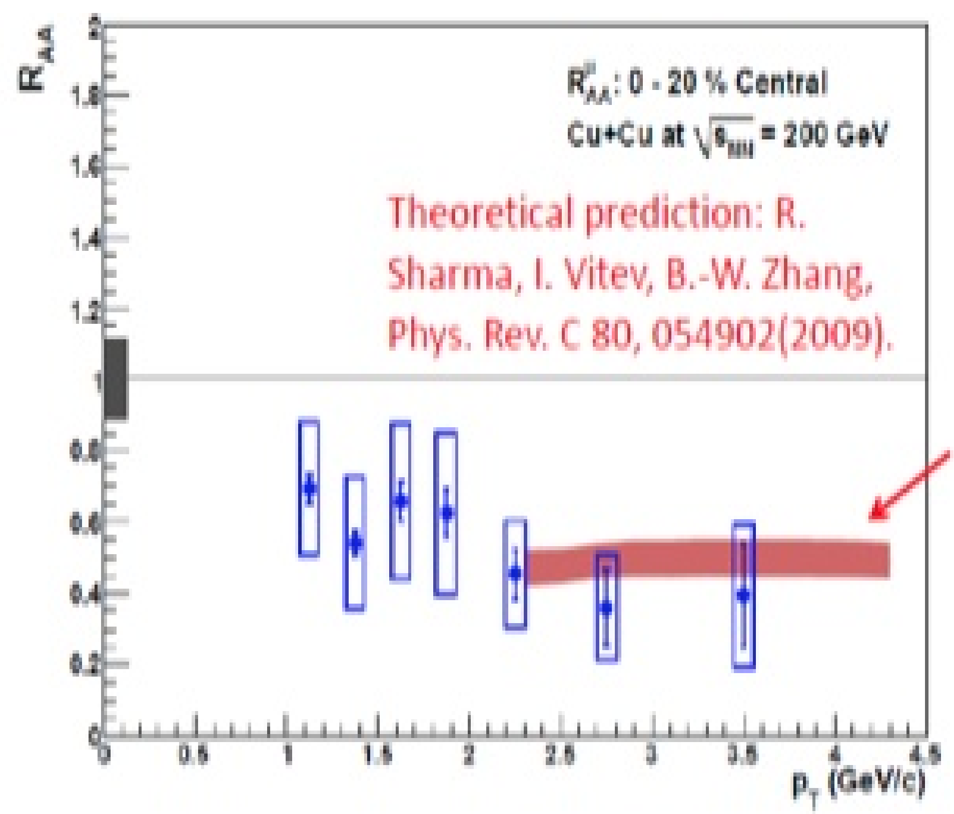
- J/ψ - non-linear turn on of shadowing with Au thickness.
- J/ψ - models with nPDF's do not do well at backward rapidity.
- J/ψ – coherent scattering model does well at forward rapidity.
- Υ(1S+2S+3S) suppressed at forward rapidity – similar to J/ψ!
- This is important to remember when evaluating Υ(2S) and Υ(3S) suppression at LHC. Is it due to the medium or CNM effects?

Heavy ion collisions

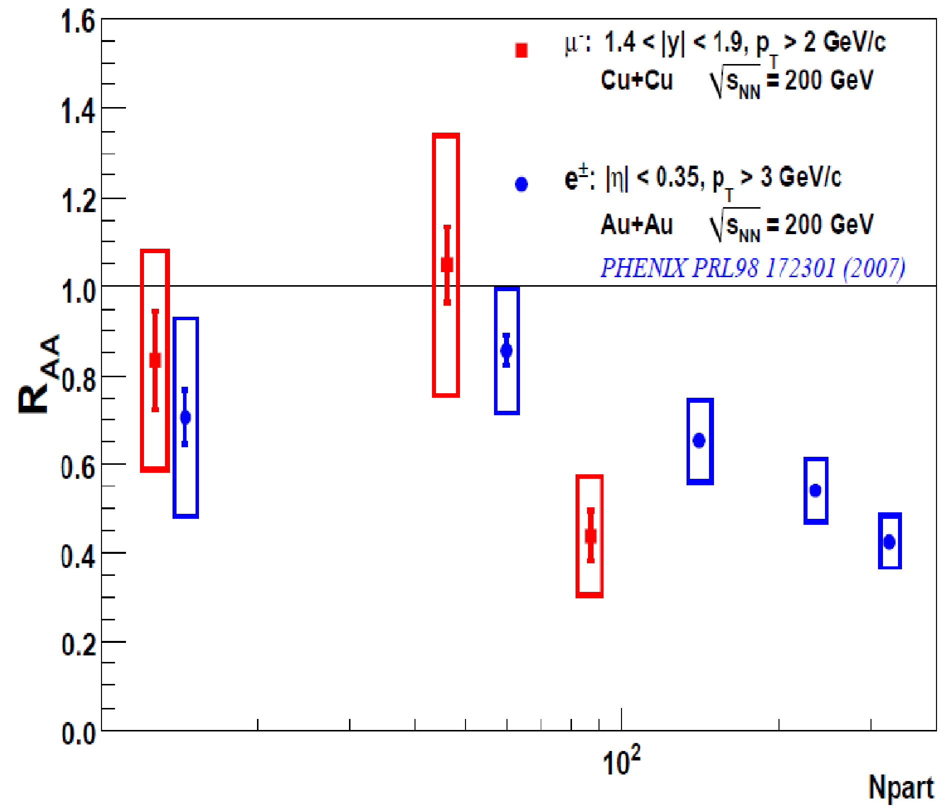
New open HF result – R_{CuCu} at forward rapidity

The first HI open heavy flavor result from the muon arms.
Shows strong suppression for 0-20% Cu+Cu centrality.
See Ken Read's talk.

R_{CuCu} at y=1.7 vs p_T



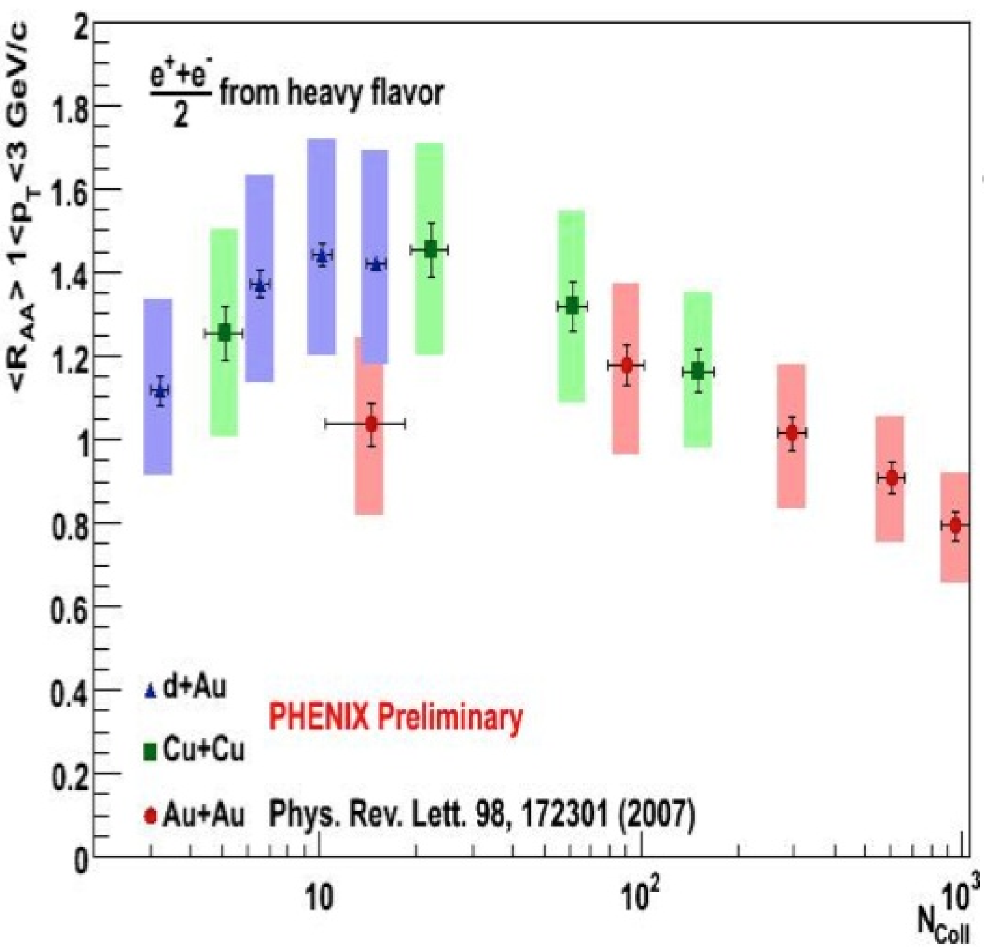
R_{CuCu}(y=1.7) for p_T > 2 GeV/c
R_{auAu}(y=0) for p_T > 3 GeV/c



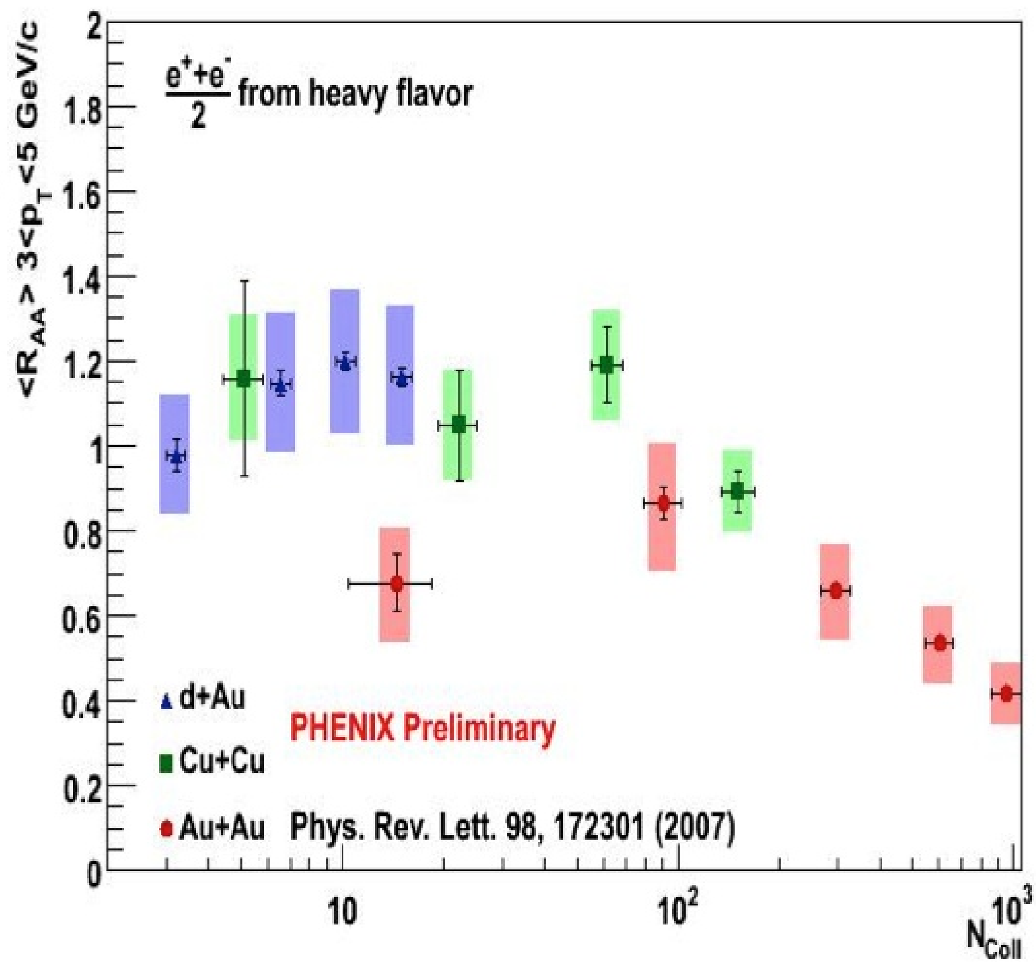
Open Heavy Flavor electron R_{CuCu} at midrapidity – shows common N_{coll} dependence with R_{dAu} and R_{AuAu}

See talk by Sourav Tafradar.

$\langle R_{AA} \rangle$ for $1<p_T<3$ GeV/c

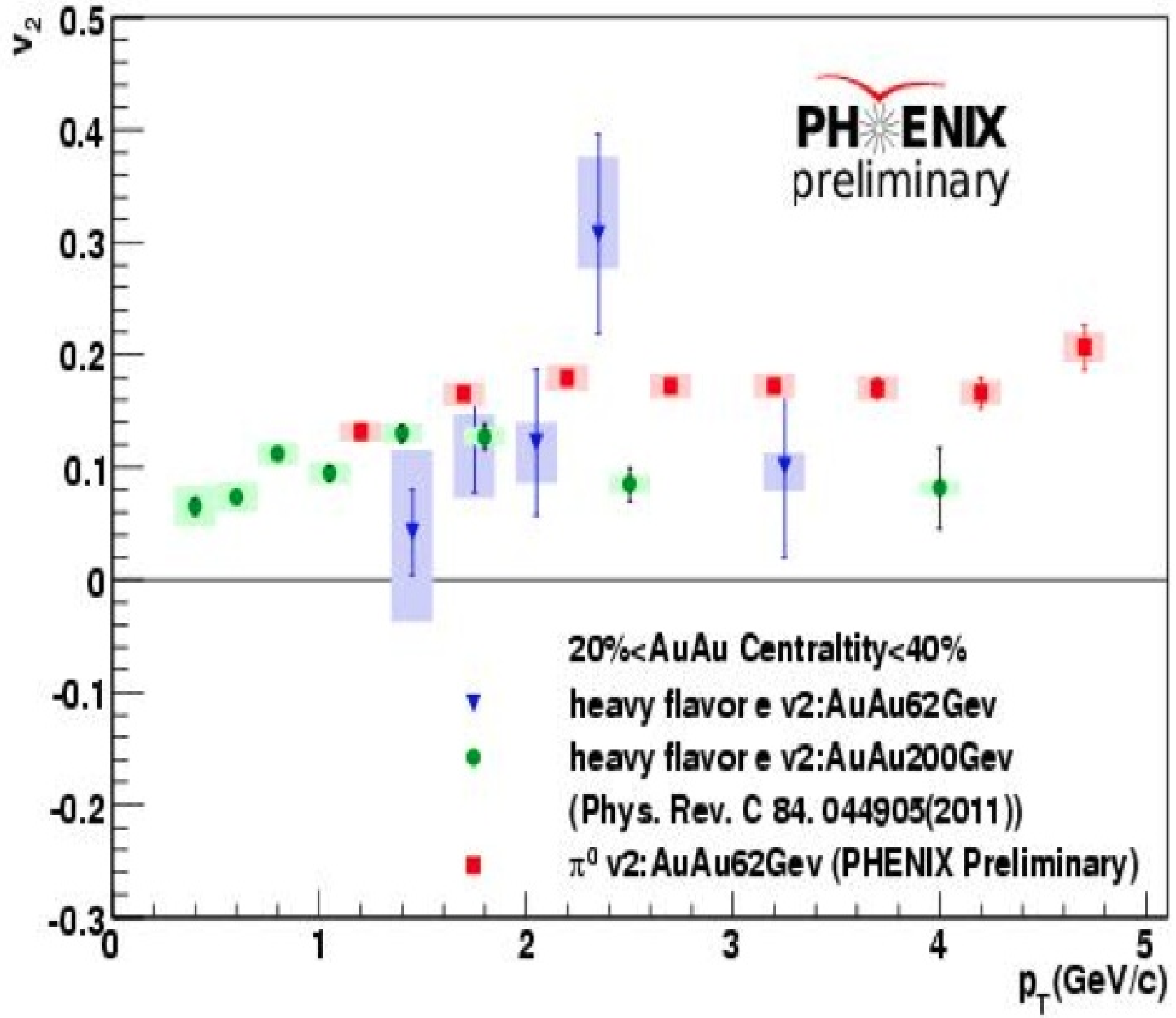


$\langle R_{AA} \rangle$ for $3<p_T<5$ GeV/c



Heavy flavor v_2 at $\sqrt{s_{NN}} = 62$ GeV

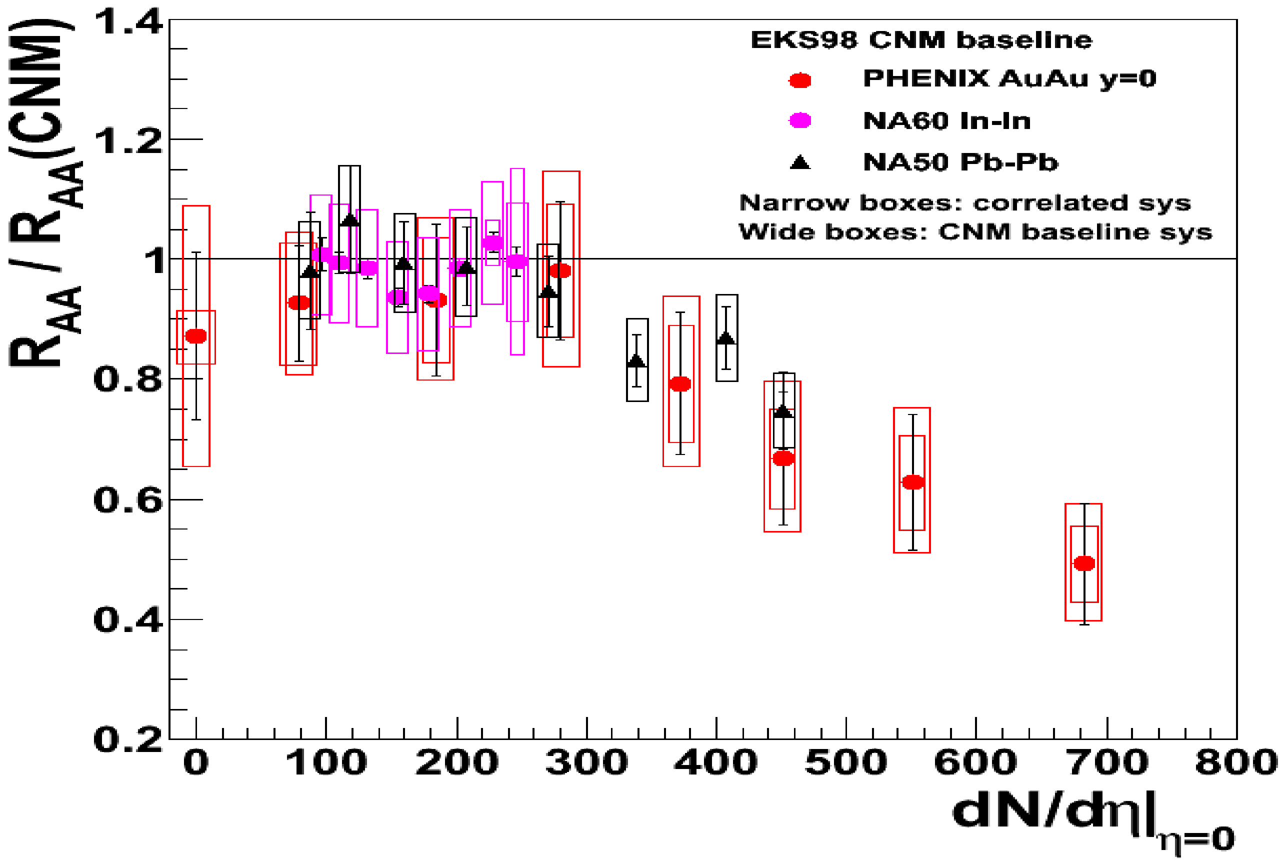
The semileptonic decay v_2 at 62 GeV seems comparable to 200 GeV.
See talk by Sourav Tafradar.



Correcting R_{AA} for CNM effects at midrapidity

Fit $\sigma_{breakup}$ to p(d)+A data (with EKS98) estimate R_{AA}(CNM)

R_{AA}/R_{AA}(CNM) for PHENIX Au+Au, NA60 In+In, Pb+Pb (arXiv:0907.5004)



Assuming factorization: suppression ~ 25% at SPS, ~ 50% at RHIC

Correcting R_{AA} for CNM effects at midrapidity

Fit $\sigma_{breakup}$ to p(d)+A data (with EKS98) estimate R_{AA}(CNM)

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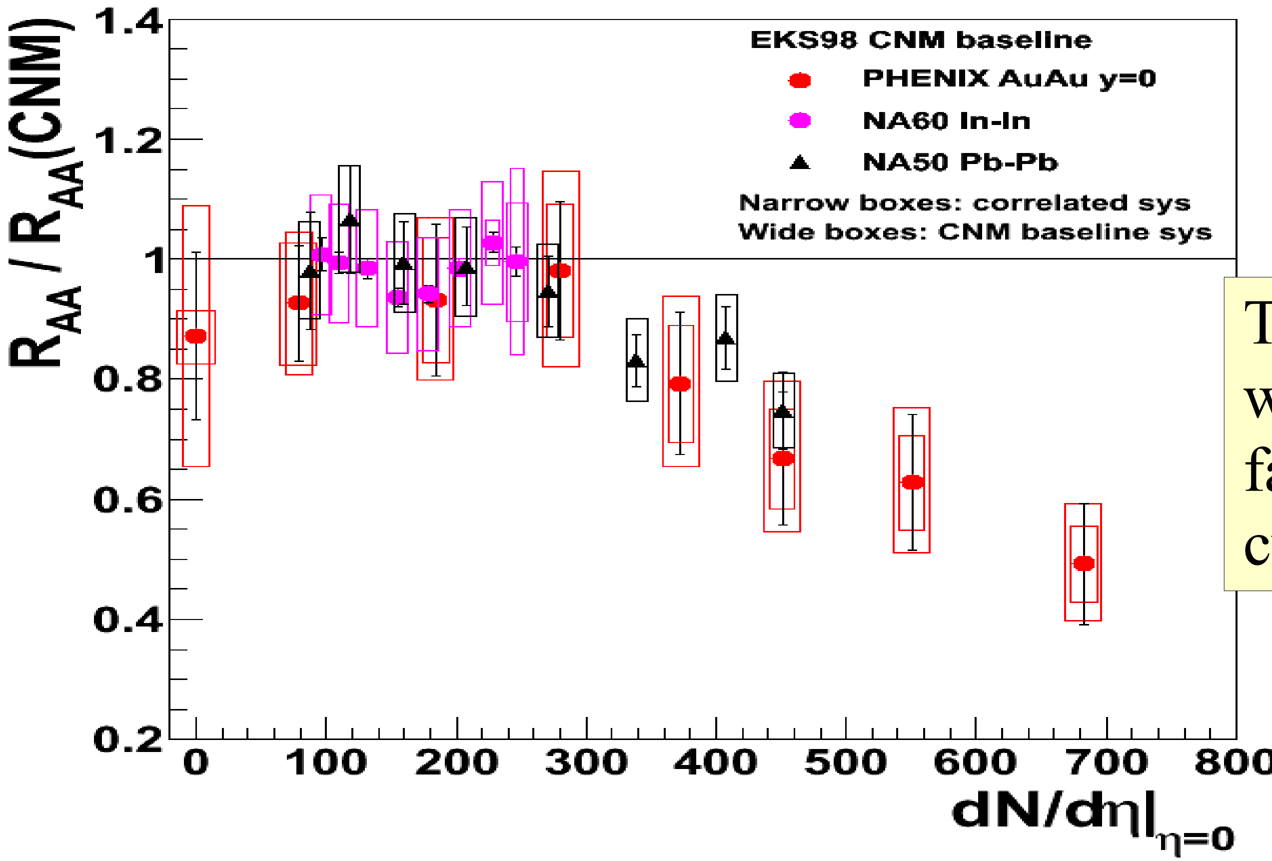


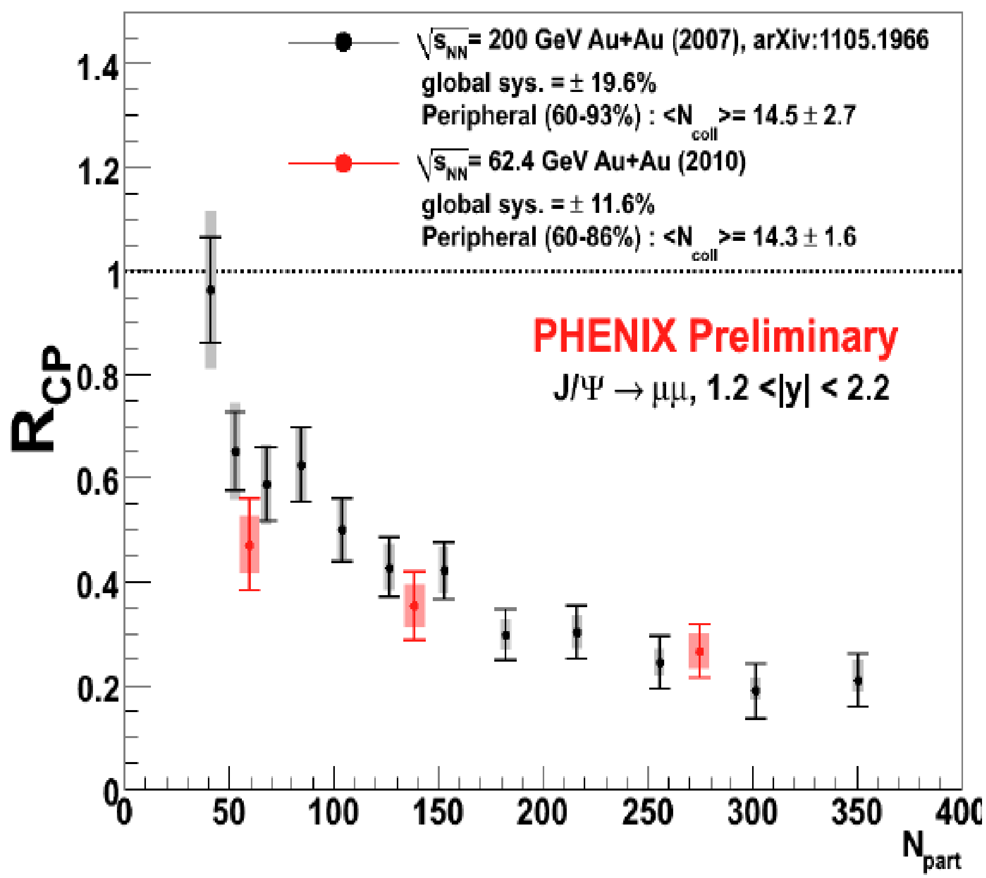
The ALICE data will likely not fall on this curve!

Assuming factorization: suppression ~ 25% at SPS, ~ 50% at RHIC

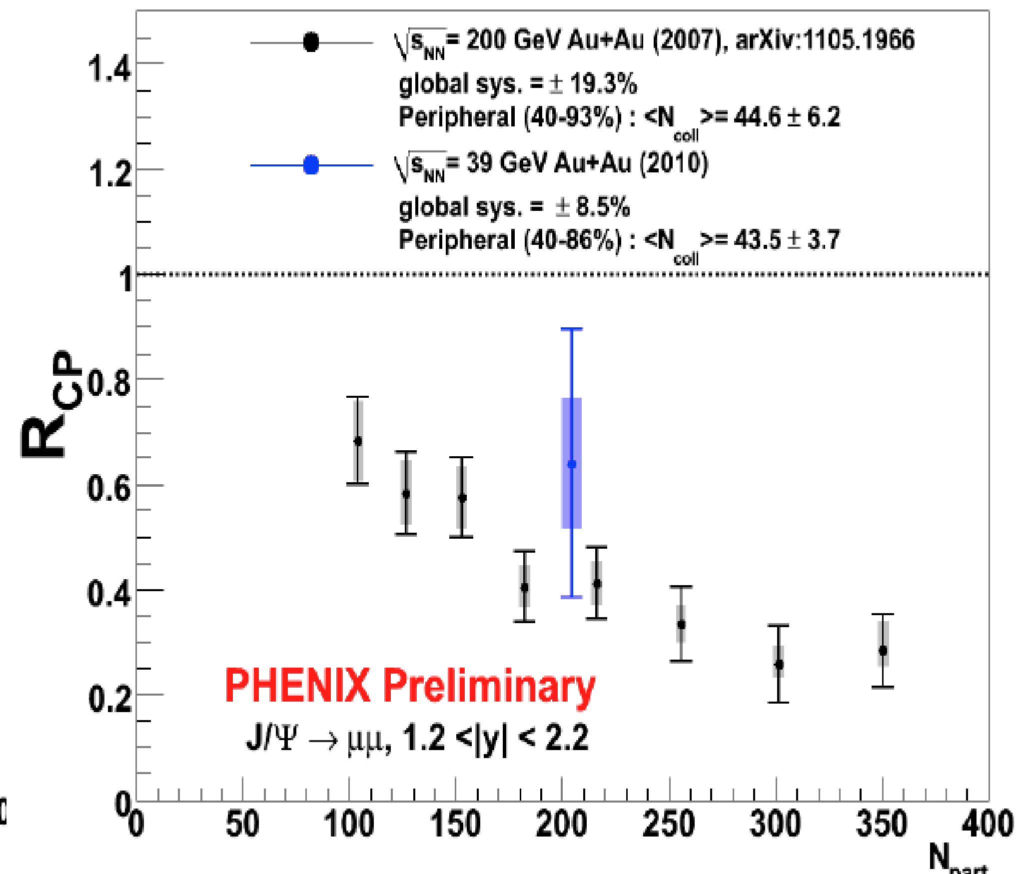
Lower energy J/ψ measurements

We show R_{CP} for now, since we don't have p+p reference data yet.
Suppression at 62 GeV is very similar to 200 GeV.

$\sqrt{s_{NN}}$=62 GeV



$\sqrt{s_{NN}}$=39 GeV



Lower energy J/ψ measurements

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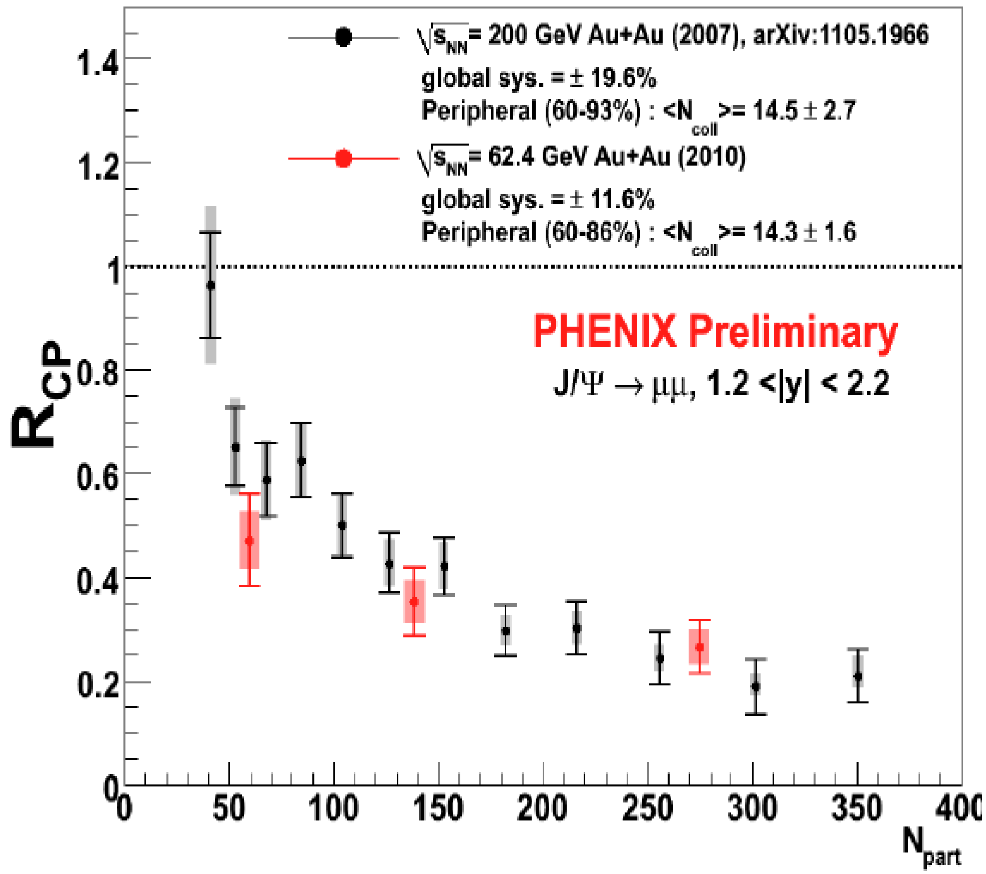
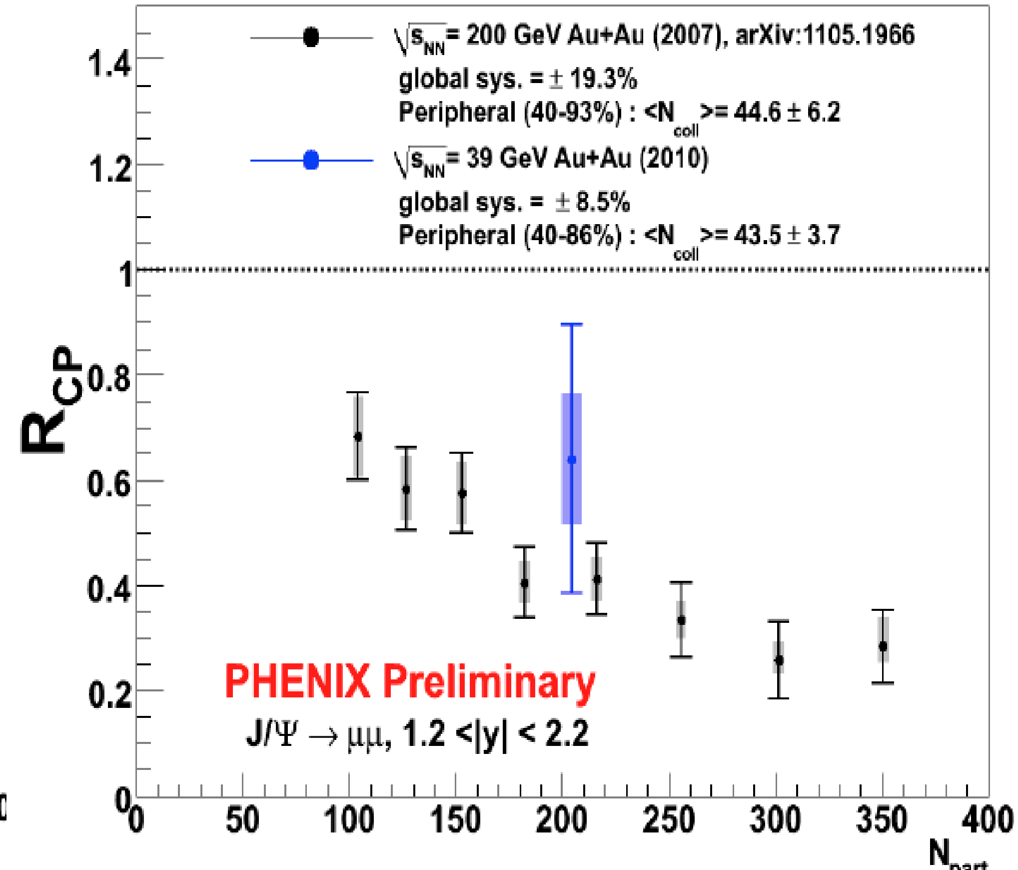
Suppression at 62 GeV is very similar to 200 GeV.

But ....

$\sqrt{s_{NN}}$=62 GeV



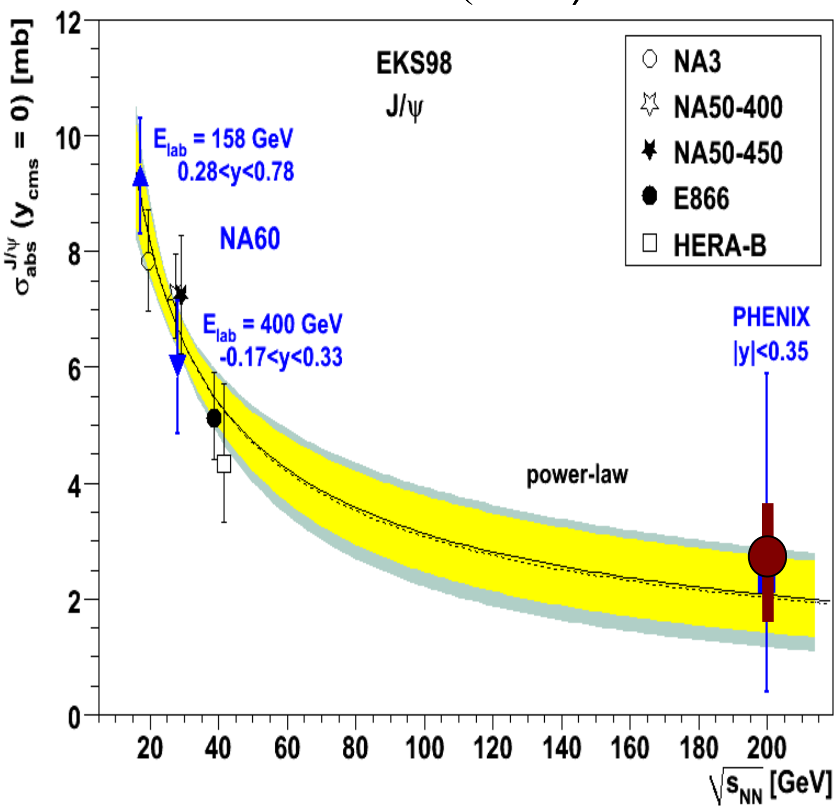
$\sqrt{s_{NN}}$=39 GeV

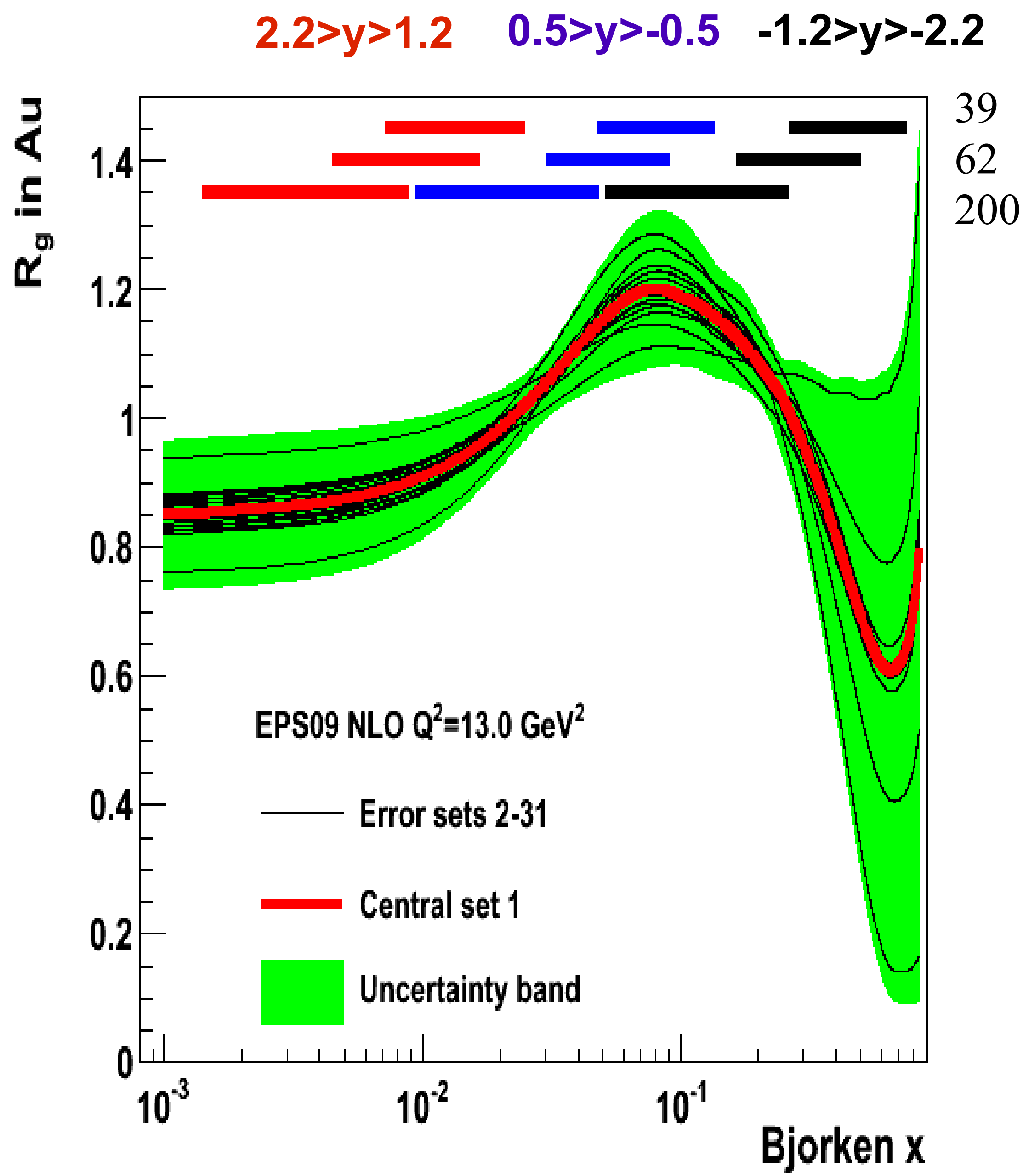


Lower collision energy J/ψ have different CNM effects!

We need to **estimate** CNM effects at lower energies, until we get low energy d+Au data.

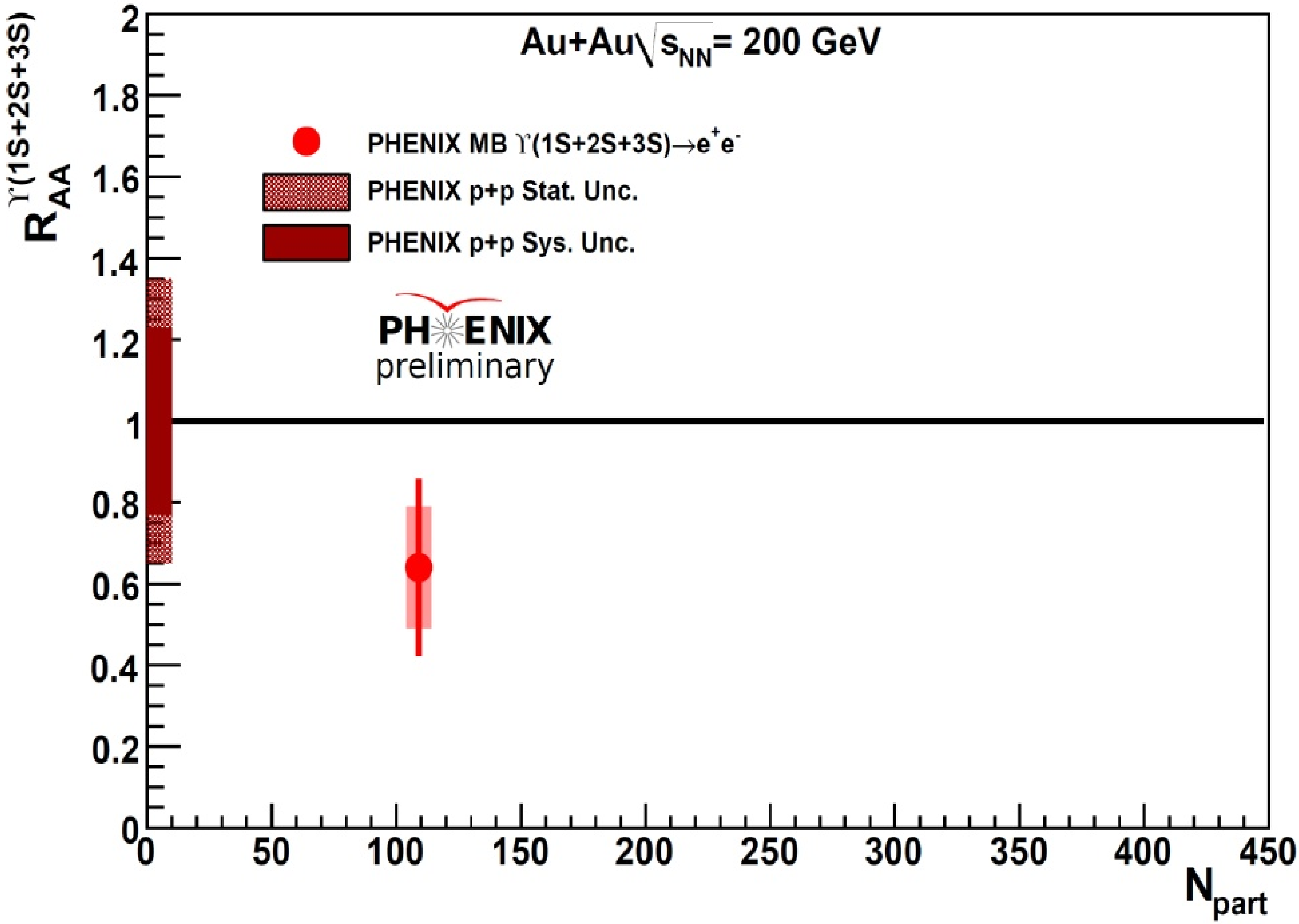
JHEP 0902:014 (2009)





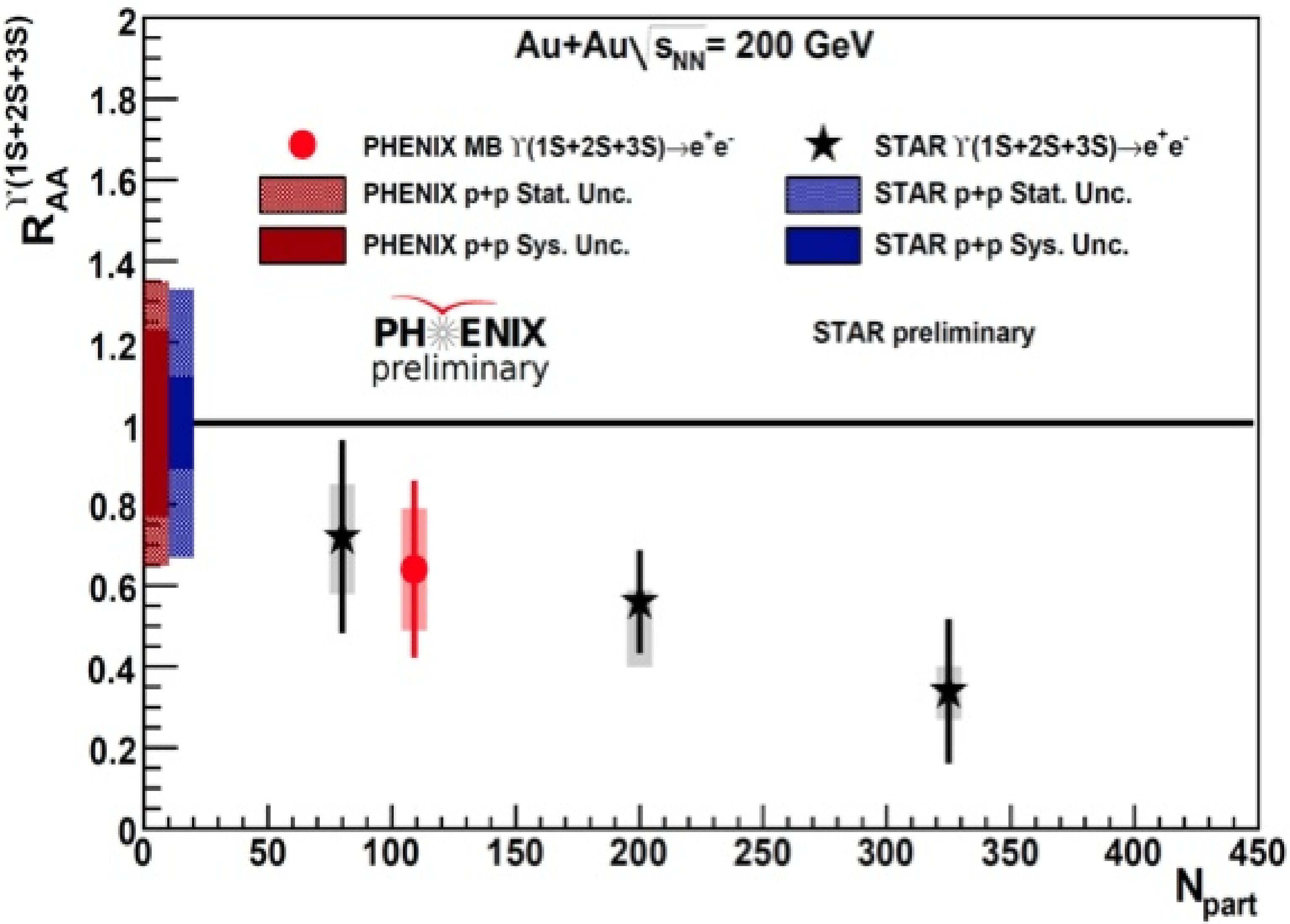
Upsilon(1S+2S+3S) Au+Au R_{AA}

Indicates suppression at y=0. See talk by Shawn Whitaker.



Upsilon(1S+2S+3S) Au+Au R_{AA}

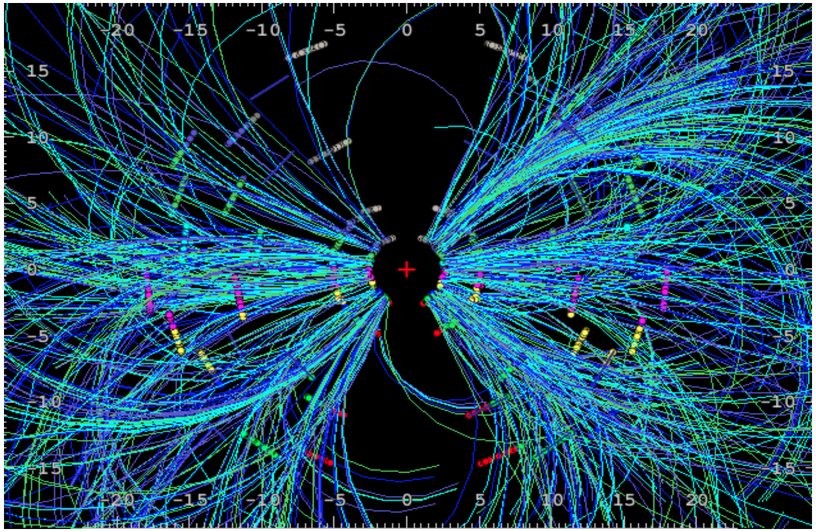
Indicates suppression at y=0. See talk by Shawn Whitaker.
Agrees well with STAR data.



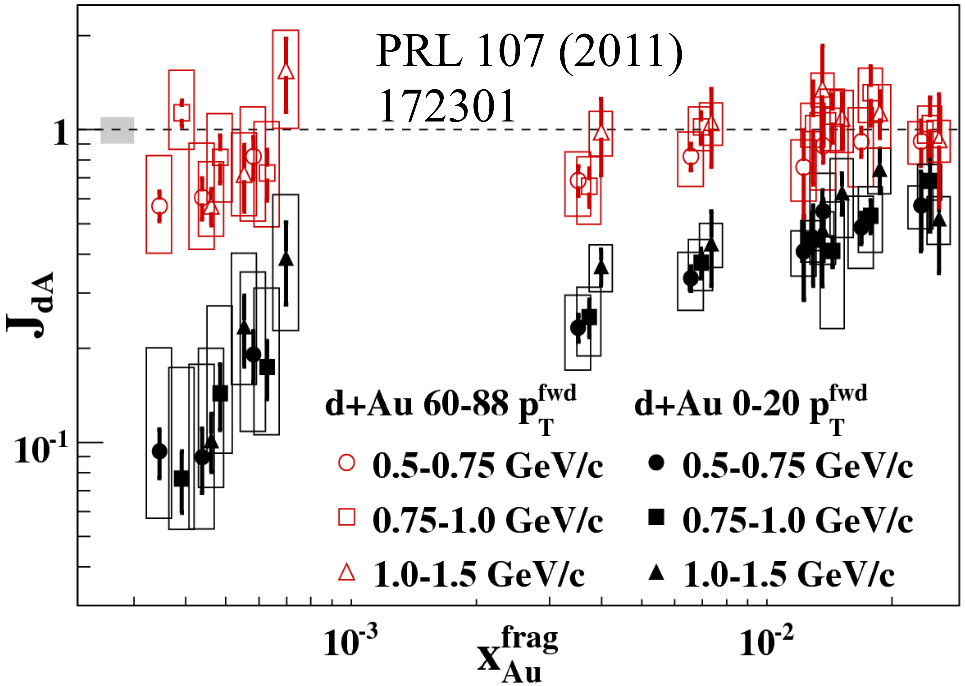
Focus of measurements in the next 5 years or so

The VTX detector (Run 11) and FVTX detector (Run 12) will allow **separated D and B** semileptonic decay measurements for p+p, d(p)+Au, and Au+Au.

Au+Au collision



They will also improve the momentum/mass resolution, helpful for some quarkonium measurements – will allow **ψ' separation** in the muon arms, for example.



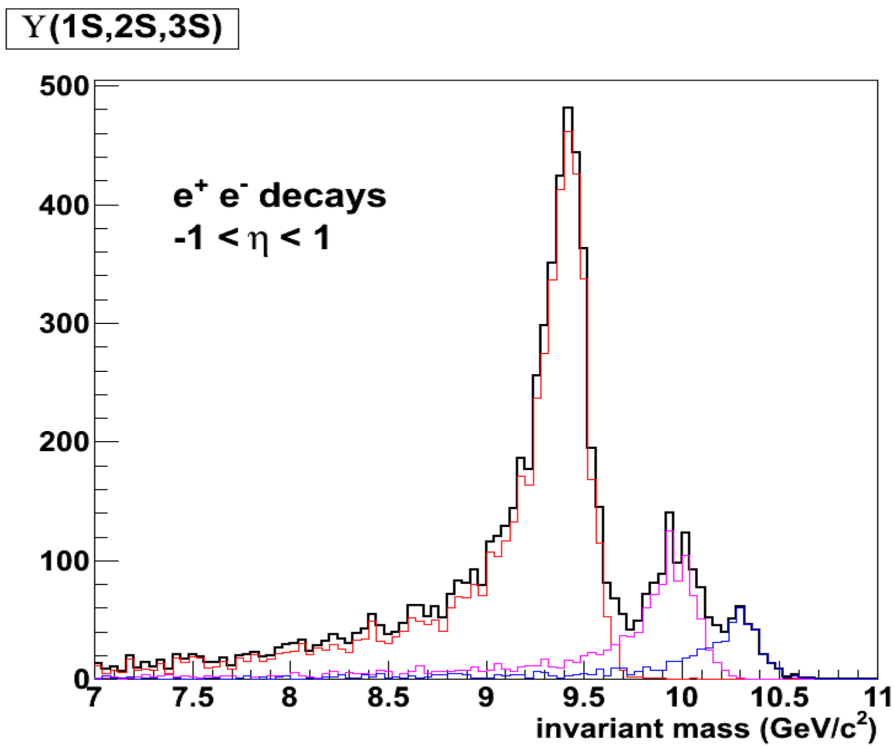
We need to tie together forward measurements using different probes!
Do they all tell the same story?

Longer term: sPHENIX

For **quarkonia**, our major goal has always been the **characterization of the Debye screening as a function of temperature**.

The SPS, RHIC and LHC J/ψ results have already shown the value of high quality **data covering a broad range of initial temperatures**.

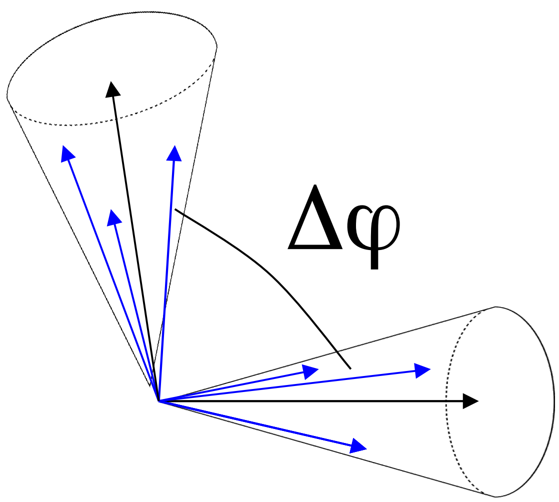
The proposed large acceptance **sPHENIX** detector, which is designed as a **jet detector**, could also – with added tracking and electron ID, make good **separated Upsilon measurements**.



For sPHENIX see talks by Rich Seto and Brian Cole.

Backup

Forward rapidity, back-to-back di-hadron measurement in d+Au



$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

Caveats:

1. Low p_T (but back-to-back peak is selected)
2. Di-Hadrons not di-jets (but ok if fragmentation unmodified)

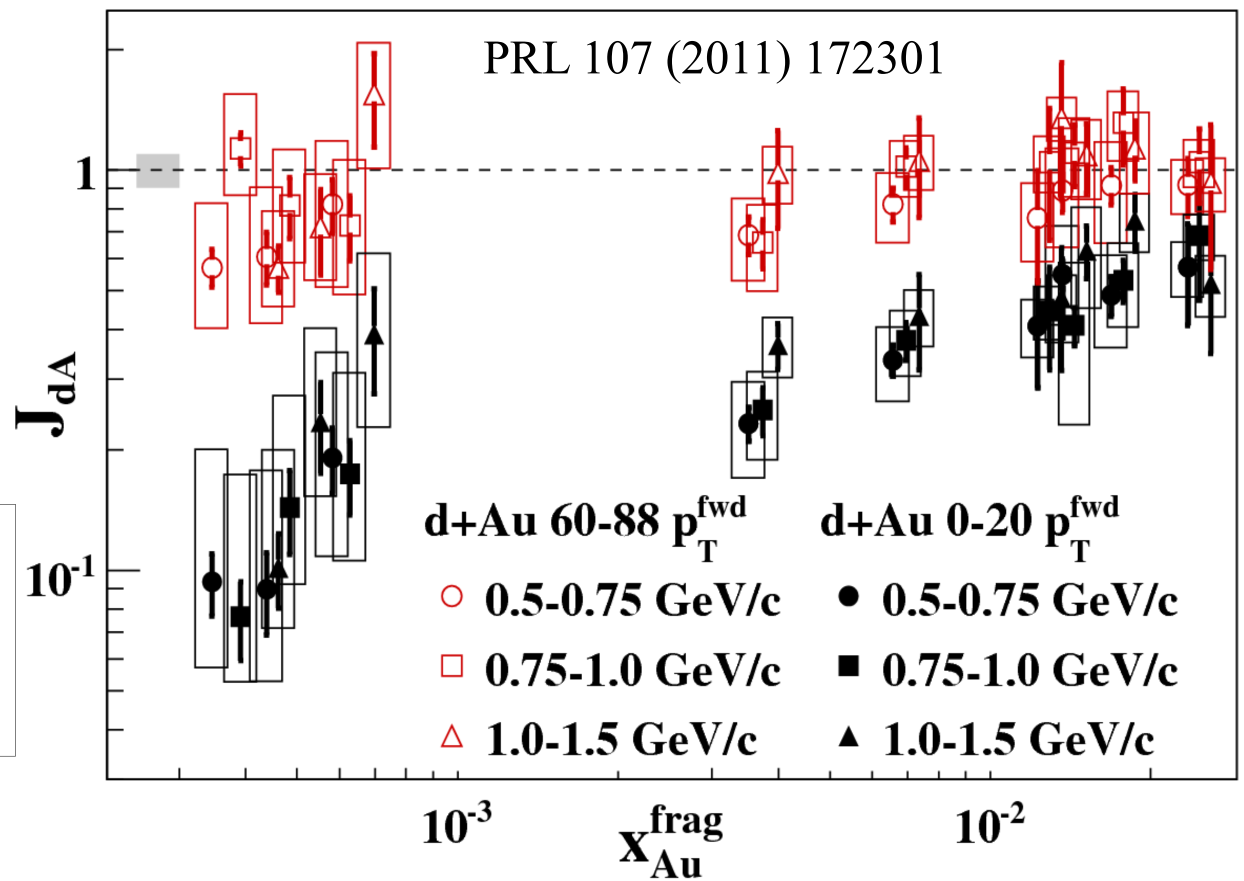
We do not know Bjorken x in the Au nucleus unless the two hadrons carry all of the parton energy. Instead, use:

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-\eta_1} + < p_{T2} > e^{-\eta_2}}{\sqrt{S_{NN}}}$$

$$J_{dA} \propto \frac{f_d^a(x_d) \otimes f_{Au}^b(x_{Au}) \otimes \sigma^{ab \to cd} \otimes D(z_c, z_d)}{f_p^a(x_p) \otimes f_p^b(x_p) \otimes \sigma^{ab \to cd} \otimes D(z_c, z_d)}$$

High x, mostly quarks
Weak effects expected

Low x, mostly gluons $\rightarrow J_{dA} \leftrightarrow R_G^{Au}$



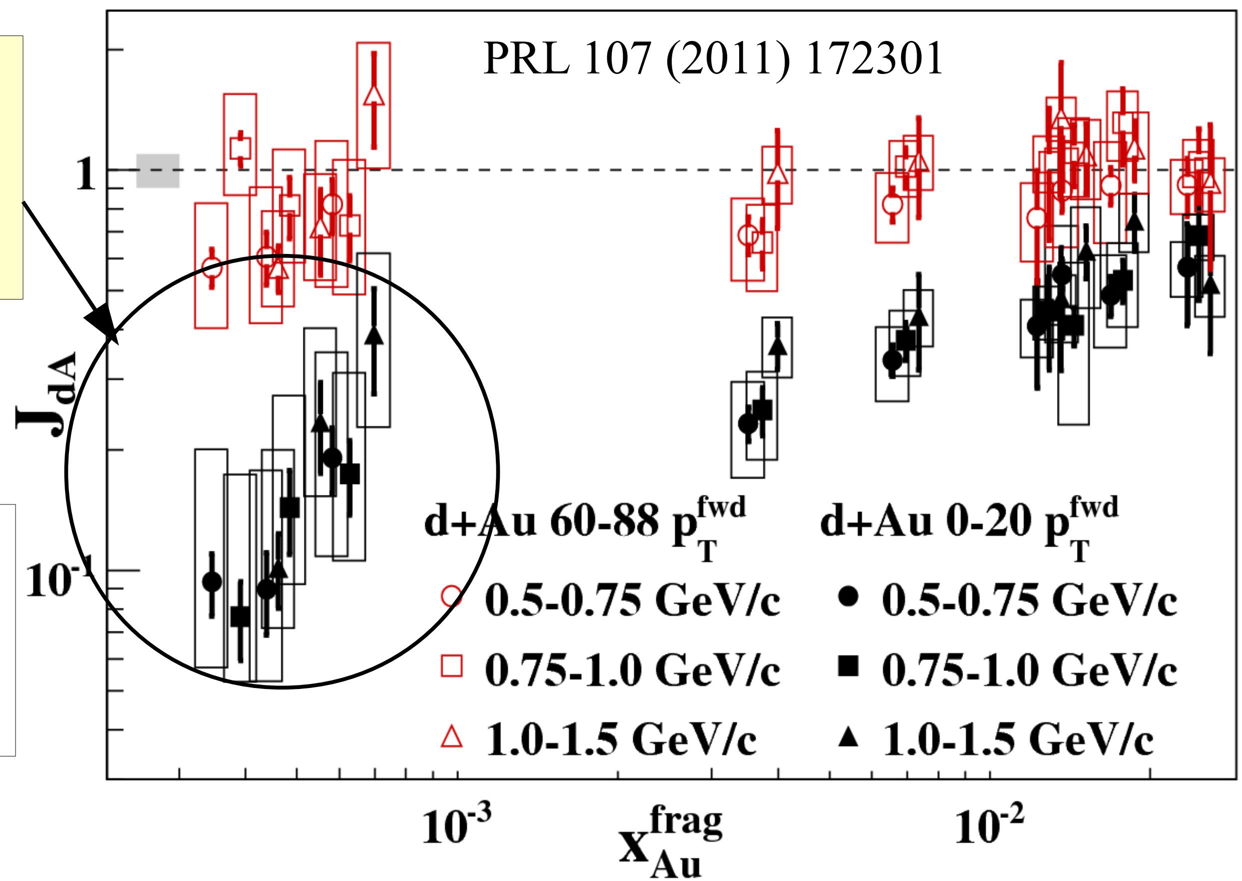
Very strong suppression at low values of x_{frag} for central collisions.

$$J_{dA} \propto \frac{\boxed{f_d^a(x_d)} \otimes \boxed{f_{Au}^b(x_{Au})} \otimes \sigma^{ab\to cd} \otimes D(z_c, z_d)}{\boxed{f_p^a(x_p)} \otimes \boxed{f_p^b(x_p)} \otimes \sigma^{ab\to cd} \otimes D(z_c, z_d)}$$

High x, mostly quarks
Weak effects expected

Low x, mostly gluons $\rightarrow J_{dA} \leftrightarrow R_G^{Au}$

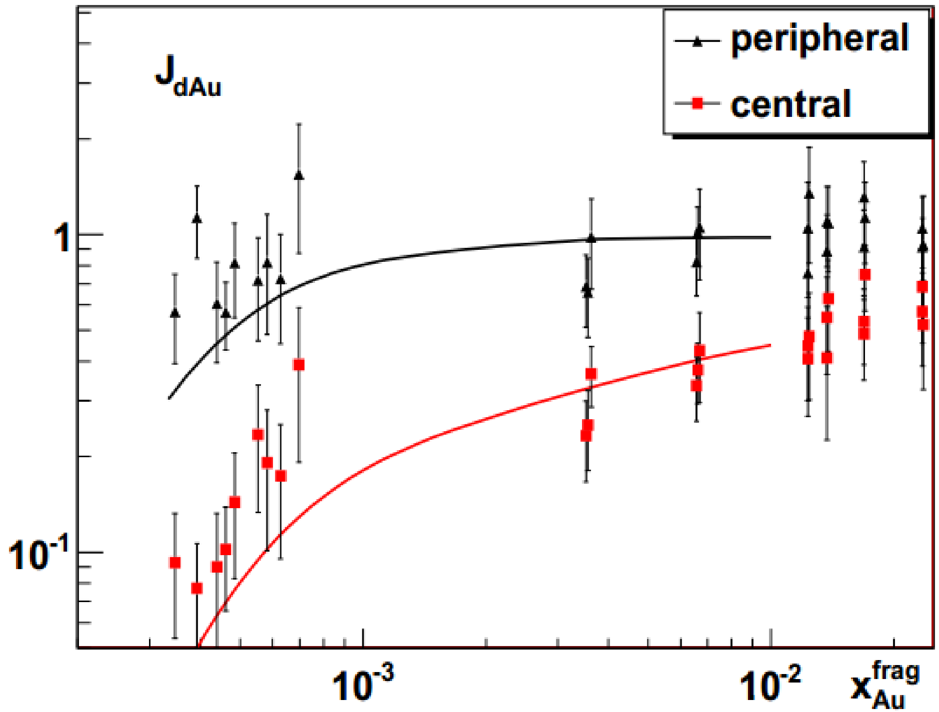
Note: x_{frag} here lower than lowest x in J/ψ case. But in general z < 1, and x > x_{frag}.



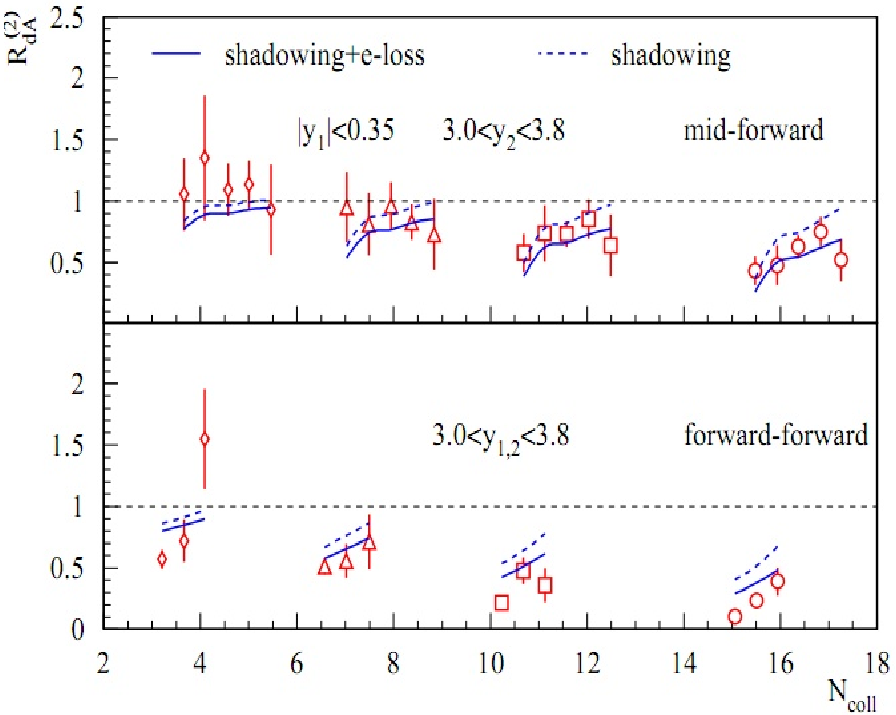
Very strong suppression at low values of x_{frag} for central collisions.

CGC vs "pQCD" Approach

Stasto, Xiao, Yuan [arxiv:1109.1817]



Kang, Vitev, Xing [arxiv:1112.6021]



•Left: CGC saturation approach
•Right: Perturbative approach incorporates ISI and FSI for momentum imbalance (multiple scattering broadening), plus energy loss and coherent power corrections

•Win-win scenario? Either saturation is found, or one can extract $g_{Au}(x)$.

Conclusions from d+Au data

Open heavy flavor:

- No suppression for 1-5 GeV/c, likely some enhancement.
- Final data out soon, VTX data next d+Au run!

Quarkonium:

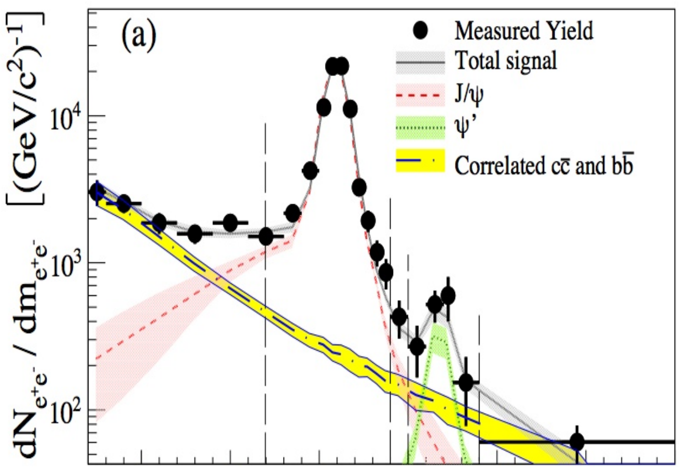
- J/ψ - non-linear turn on of shadowing with Au thickness.
- J/ψ - models with nPDF's do not do well at backward rapidity.
- J/ψ – coherent scattering model does well at forward rapidity.
- Υ(1S+2S+3S) suppressed at forward rapidity – similar to J/ψ!

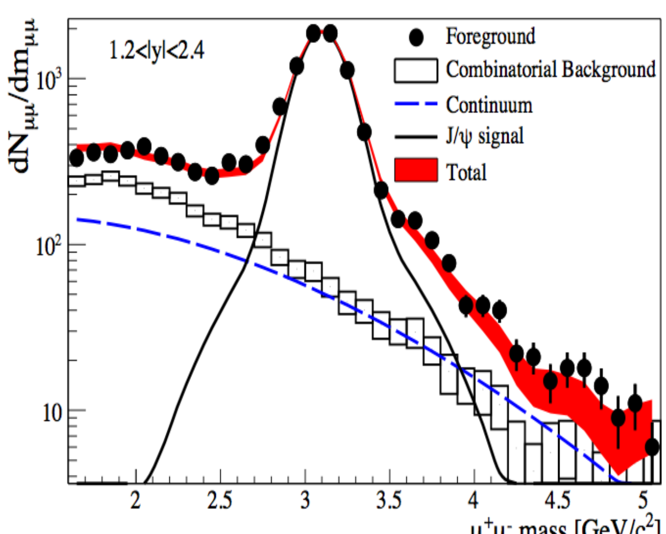
Forward/forward and forward/mid dihadrons:

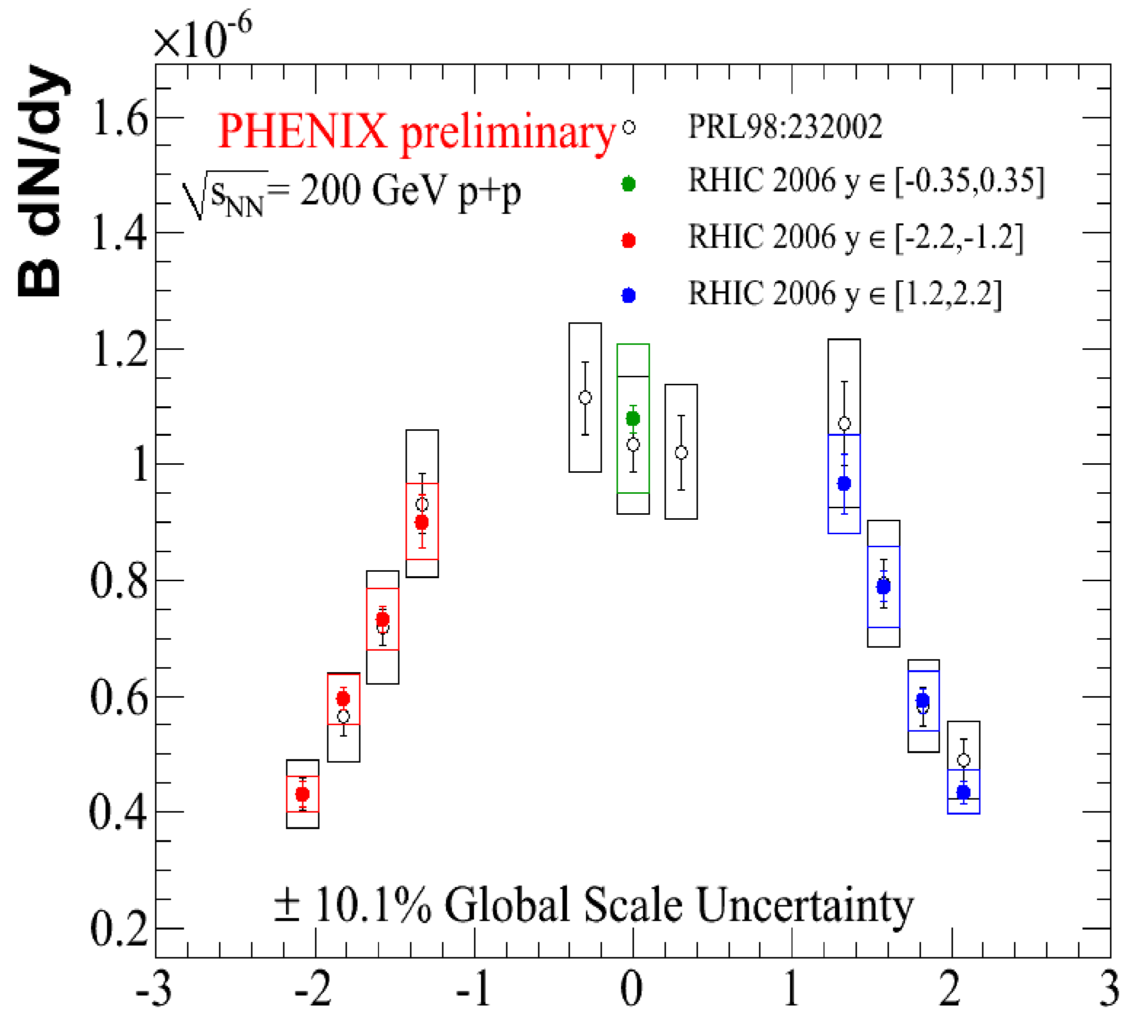
- Forward/forward dihadrons much stronger suppression than J/ψ
- Access lower x than J/ψ (?)
- Described by CGC or perturbative approach.

p+p collisions – rapidity distribution

Before we can measure modifications in nuclear collisions, we have to measure the baseline cross sections in p+p collisions.







$$BR\,\sigma_{J/\psi} = 180.7 \pm 2 \pm 12\,nb$$

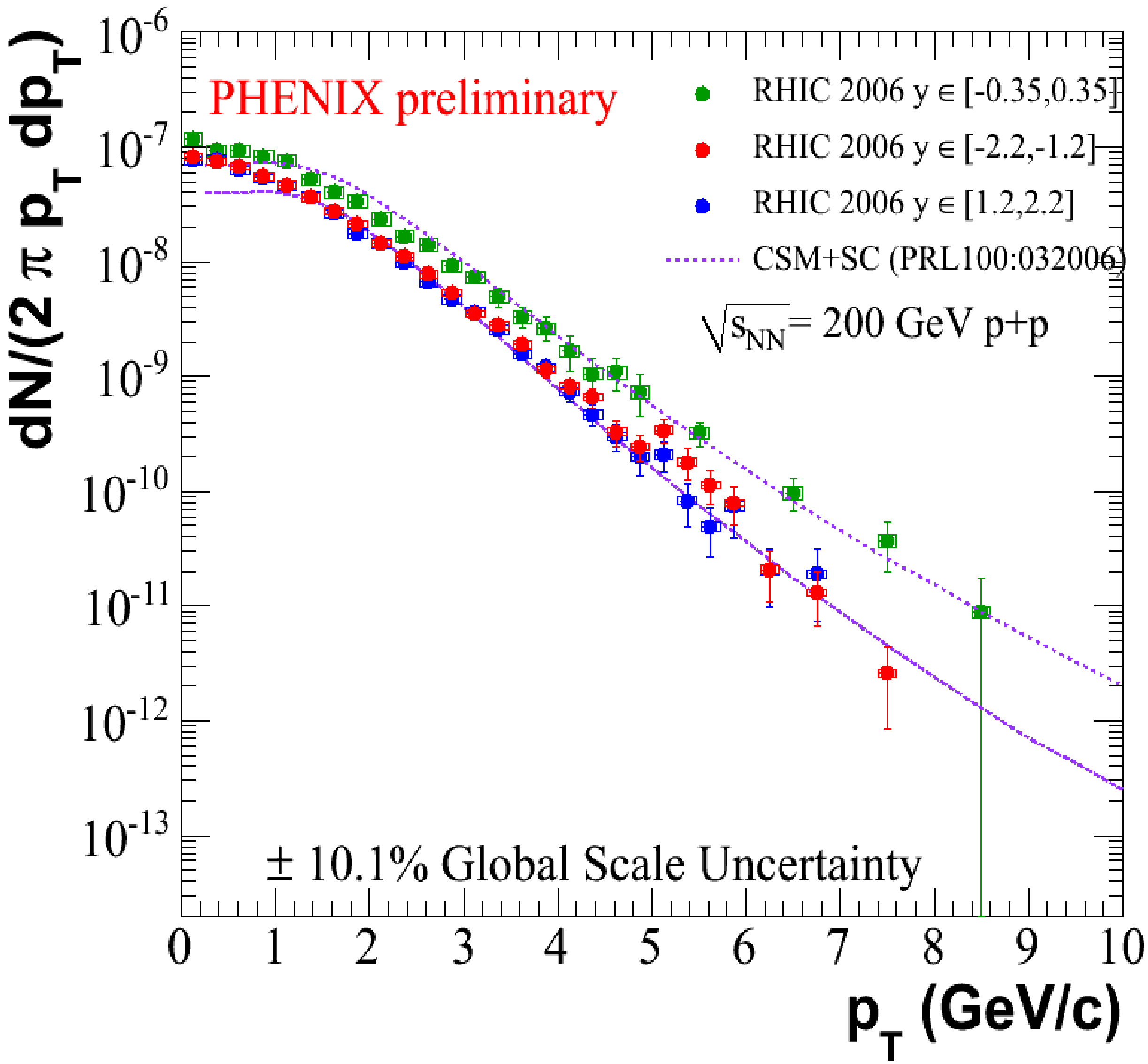
p+p collisions – transverse momentum

The p_T distributions for the three PHENIX spectrometers.

The distribution is noticably harder at midrapidity.

Fortunately, it is the same at forward and backward rapidity.

These distributions (appropriately binned or integrated in p_T and y) provide the denominators for all of our R_{dAu} data.



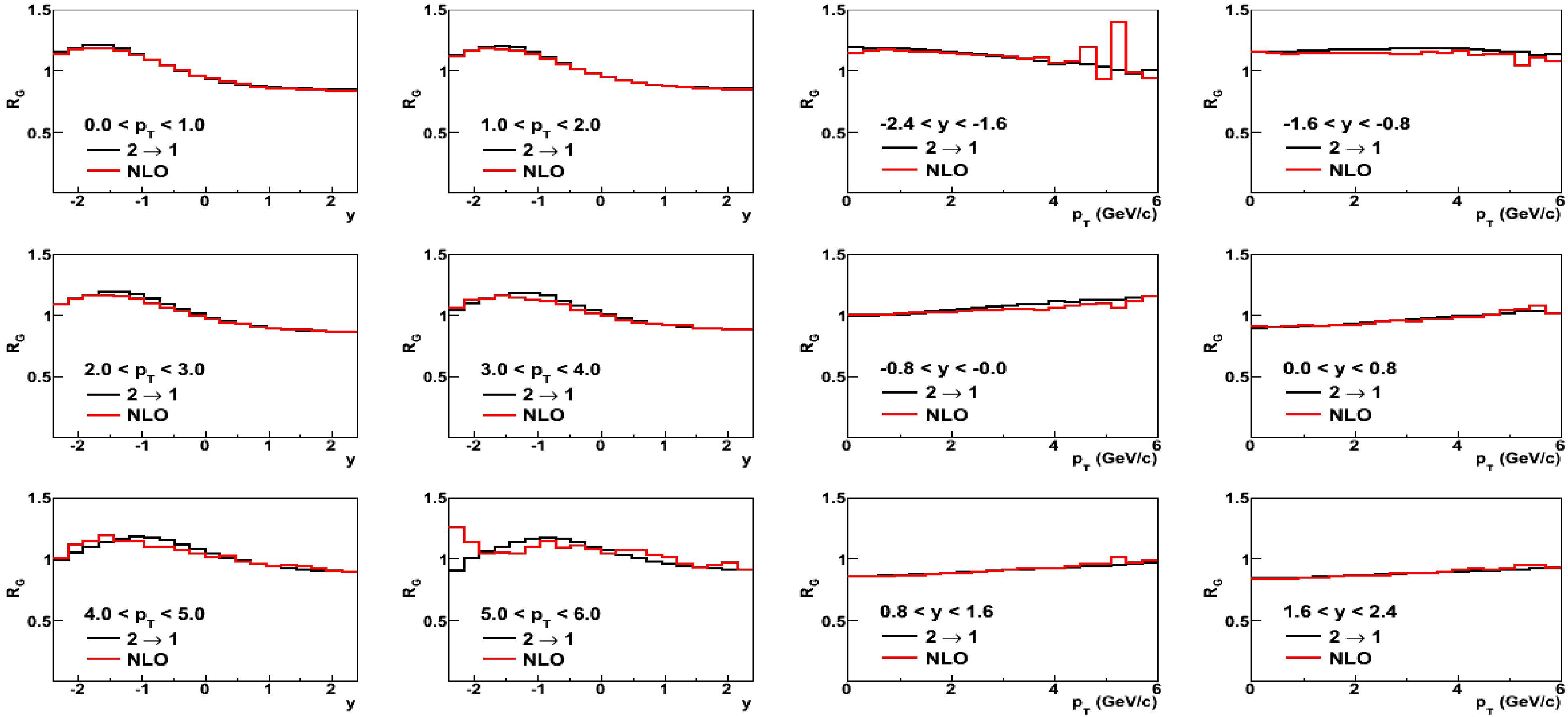
How do we get x_2 and Q^2 for use with EPS09?

We assume **2→1 kinematics**.

$$x_2 = \frac{\sqrt{M_J^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y}$$

Not quite correct - but R_G obtained with x_2 and Q^2 from an NLO calculation by Ramona Vogt is very similar.

$$Q^2 = M_{J/\psi}^2 + p_T^2$$



Heavy ion data – J/ψ production at 200 GeV

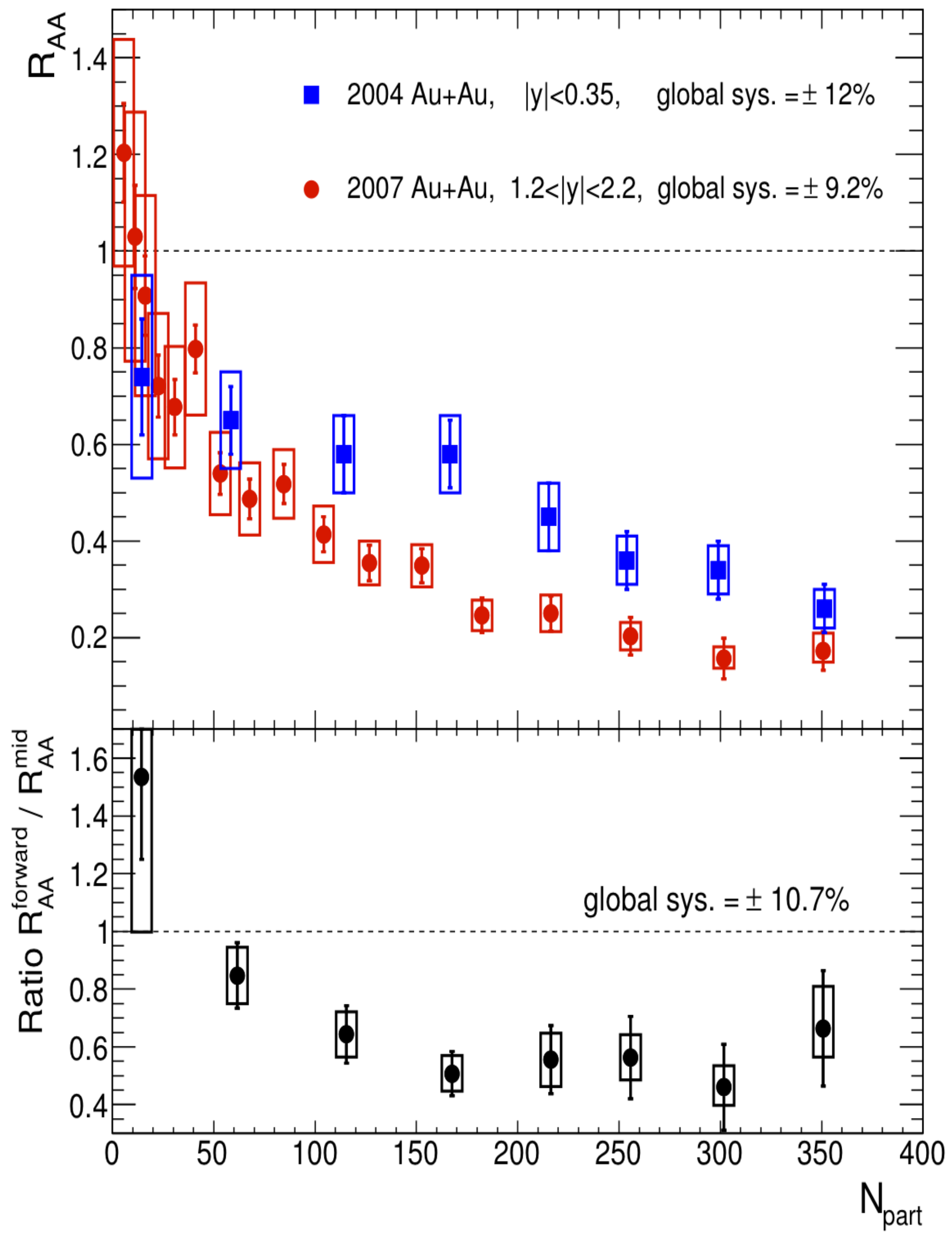
Substantially stronger suppression at forward rapidity. But we know that CNM effects are strong!

Can we correct for CNM effects?

At midrapidity, where shadowing is weak at RHIC energies, dAu data are described **reasonably well** by nPDF's + fitted σ_{br}..

At backward rapidity, description of R_{dAu} **poor for all calculations**. Also nonlinear centrality dependence. Need better understanding at |y|=1.7.

If CNM effects factorize, probably can **correct at y=0**, not at y=1.7.

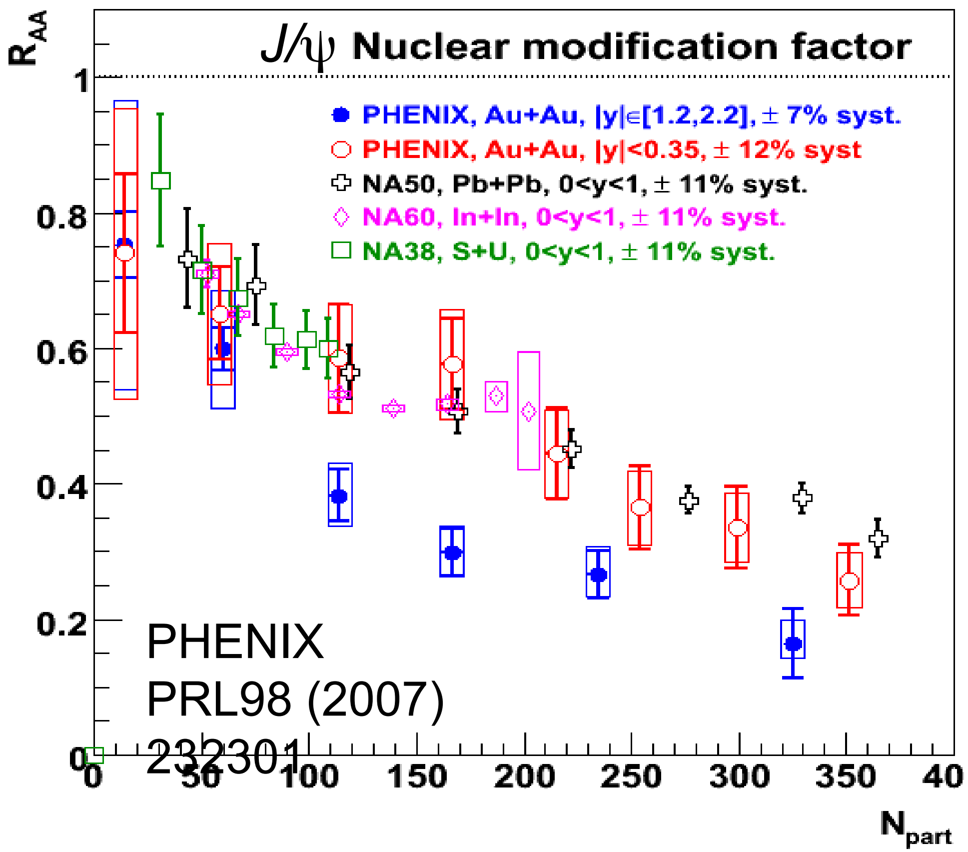


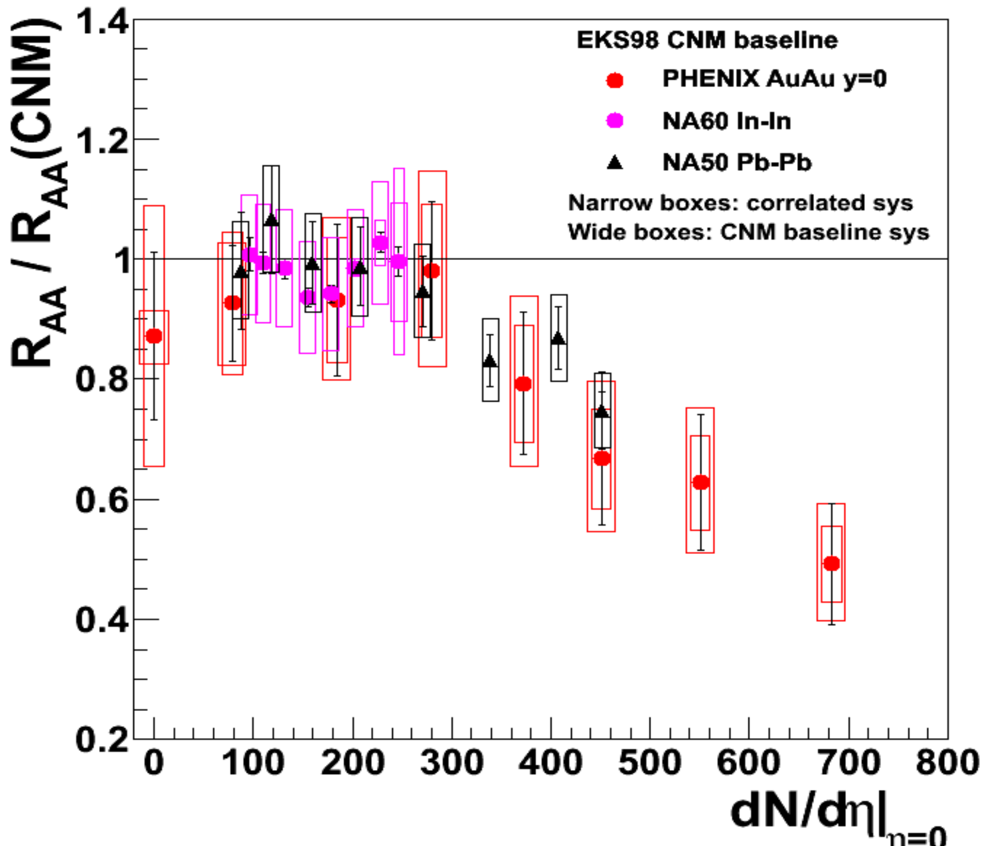
Correcting R_{AA} for CNM effects at midrapidity

Fit p(d)+A data with EKS98 + $\sigma_{breakup}$, estimate R_{AA}(CNM)

Without CNM correction, suppression same at RHIC and SPS!

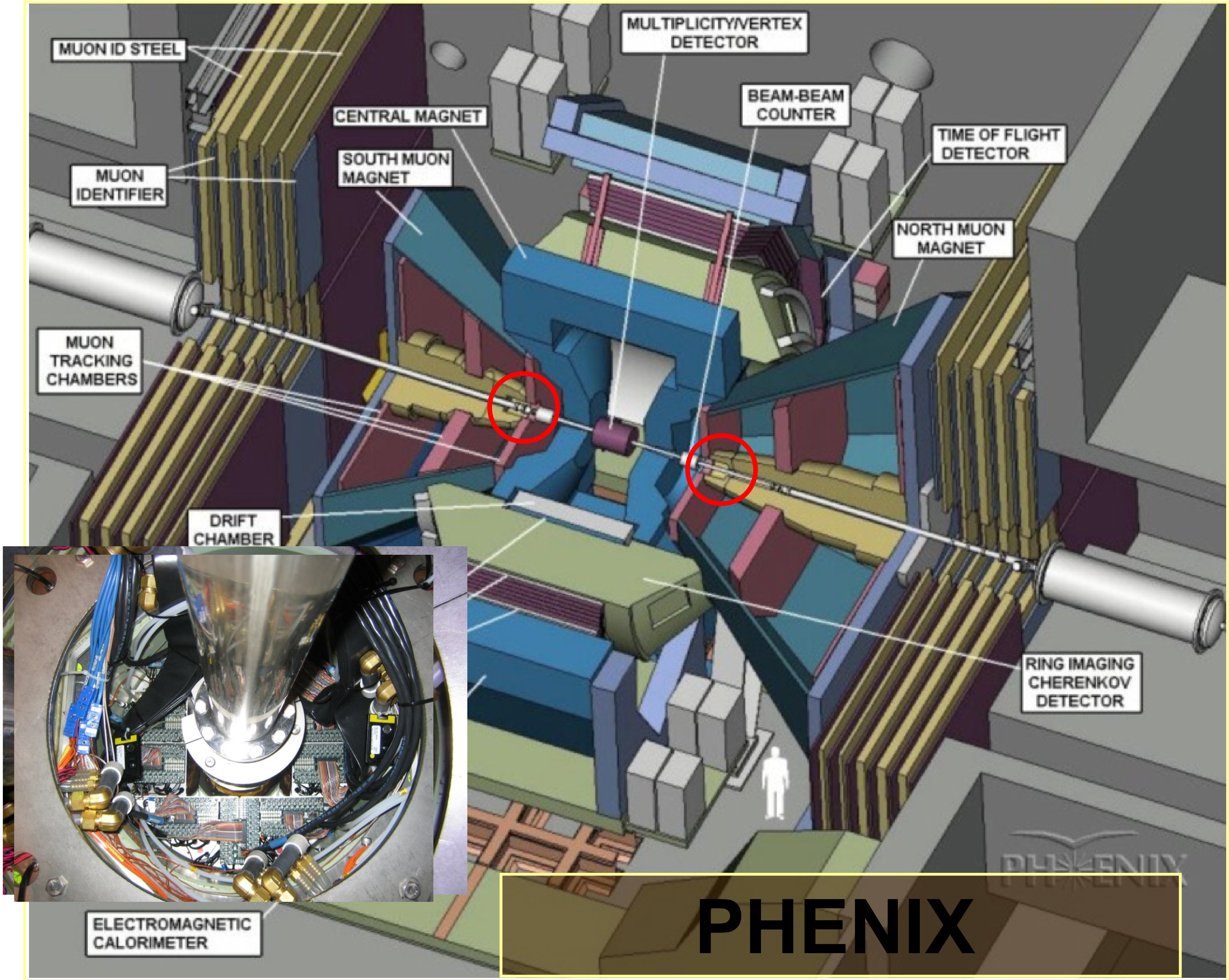
PHENIX Au+Au, NA60 In+In, Pb+Pb (arXiv:0907.5004) **R_{AA}/R_{AA}(CNM)**





Suppression ~ 25% at SPS, ~ 50% at RHIC

Forward π^0's – Muon Piston Calorimeter ($3.0<|\eta|<3.8$)



Note on centrality bins

The centrality bins are **highly overlapping** in d+Au. Below is the **nucleon-Au** impact parameter (r_T) distribution from the Glauber model (normalized to unity for each centrality bin, to make comparison easier)

The overlap reflects statistical fluctuations in the BBC detector signal for a given impact parameter. It limits the impact parameter resolution.